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DEVELOPMENT OF NAVAL DIESEL ENGINE DUTY CYCLES FOR AIR EXHAUST EMISSION ENVIRONMENTAL IMPACT ANALYSIS

by

Stephen Paul Markle

B.S., Environmental and Resource Engineering
State University of New York College of Environmental
Science and Forestry (1983)

Submitted to the Department of Ocean Engineering and Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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and

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ABSTRACT

A strategy for testing naval diesel engines for exhaust emissions was developed. A survey of existing international and national standard diesel engine duty cycles was conducted. All were found to be inadequate for testing and certification of engine exhaust emissions from naval diesel powered ships. Naval ship data covering 11,500 hours of engine operation of four U.S. Navy LSD 41 Class amphibious ships was analyzed to develop a 27 point class operating profile. A procedure combining ship hull form characteristics, ship propulsion plant parameters, and ship operating profile was detailed to derive an 11-Mode duty cycle representative for testing LSD 41 Class propulsion diesel engines. A similar procedure was followed for ship service diesel engines. Comparisons with industry accepted duty cycles were conducted using exhaust emission contour plots for the Colt-Pielstick PC-4B diesel engines. Results showed the 11-Mode LSD 41 Class Duty Cycle best predicted ship propulsion engine emissions compared to the 27 point operating profile propeller curve. The procedure was applied to T-AO 187 Class with similar results. The application of civilian industry standards to measure naval diesel ship propulsion engine exhaust emissions was found to be inadequate. Engine exhaust flow chemistry post turbocharger was investigated using the SANDIA Lab computer tool *CHEMKIN*. Results showed oxidation and reduction reactions within exhaust gases are quenched in the exhaust stack. Since the exhaust stream in the stack is unreactive, emission sampling may be performed where most convenient. A proposed emission measurement scheme for LSD 41 Class ships was presented.

Thesis Supervisor: Dr. Alan J. Brown
Title: Professor
Department of Ocean Engineering

Thesis Supervisor: Dr. Victor W. Wong
Title: Lecturer
Manager, Sloan Automotive Laboratory
Department of Mechanical Engineering

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My special thanks to the commanding officers ships who graciously provided access to their logs, and welcomed me into their wardrooms on my visits to compile the class operating profile: Commander C.F. Webber (USS FORT McHENRY (LSD 43)), Commander J.R. Poplar III (USS RUSHMORE (LSD 47)), Commander M.P. Nowakowski (USS GUNSTON HALL (LSD44)), and Commander S. Gilmore (USS TORTUGA (LSD 46)).

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CHAPTER 1: INTRODUCTION

1.1 Naval Diesel Engine Background

Heat engines have been in practical use as prime movers for ship propulsion for the last 210 years. During the late eighteenth century the first steam powered ships were built. Although several operative steam powered ships were built during that time period, the *PYROSCAPHE*, built by Claude de Jouffroy d'Abbans in 1783 at Lyons, France, is generally accepted as the first successful application of steam-powered propulsion to ships.[1] These early steam plants burned a coal-gas air mixture at atmospheric pressure. Over the next 100 years the efficiency of the steam engine increased; gradually steam replaced wind power for ship propulsion.

By the late 1800's liquid fuels had gained in popularity. The efficiency of existing heat engine designs which used liquid fuels was limited. Spark ignition gasoline fueled engines were the predominate internal combustion engine in use up to this time. Auto-ignition combustion (knock) of the fuel limited the compression ratios of these engines and, therefore, their efficiency. In these engines, fuel was mixed with the intake air before entry into the engine cylinder. As the mixture was compressed in the cylinder auto-ignition of the fuel, prior to spark discharge, occurred in engines with higher compression ratios.

In 1892 Rudolf Diesel, a German engineer, patented a new type of high pressure reciprocating heat engine. In 1905 J.R. Buchi, a Swiss engineer, laid

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[1]Thomas C. Gillmer, Modern Ship Design, p. 115.

the foundation for modern exhaust gas turbocharging. In 1910 James McKechnie, an English engineer, obtained a British patent for high pressure fuel injection. These three technologies combined to make the diesel engine of today. In this engine auto-ignition became a benefit. Fuel was introduced after the in-cylinder compression of the air charge. The heat generated by the gas compression initiated combustion after fuel injection. With this engine design, higher compression ratios were possible. The amount of work available per unit of fuel burned increased, raising efficiency. The diesel engine designs of today retain efficiency advantages over both spark ignition and gas turbine internal combustion engines.

In the summer of 1913 two civilians from the New York Navy Yard, Albert Kloppenberg, a draftsman, and Ernest Delbose, an engineer, together with a US Naval Officer, Lieutenant Chester W. Nimitz, were sent to Germany. They went to observe German large diesel design, construction and ship installation techniques. Prior to this time, the U.S. Navy had only limited experience with small diesel engines used in submarines. As a result of their study, the first U.S. Navy surface ship to be powered by diesel engines, the *USS MAUMEE*, was commissioned on October 23, 1916. The hull of the ship, a new 14,500 ton oiler, had been built on the west coast of the United States and towed to the New York Navy Yard in Brooklyn, New York. There, twin 2,600-horsepower diesel engines were built and installed under the supervision of Lieutenant Nimitz. The engine

design of *MAUMEE* borrowed heavily from German technology.[2]

In the past thirty years diesel engines have replaced steam plants as the propulsion plant of choice for many commercial ships. Most U.S. Navy ships are equipped with diesel generators for emergency electrical power. Some use diesel generators for ships service electric load; a smaller number (69) have diesel main propulsion.[3]

Diesel engines procured for the navy must successfully pass the 1,000 hour durability test outlined in Military Specification MIL-E-21260D *Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed,* of March 1976. No procedure is currently specified by the Navy to test diesel engines for exhaust emissions during the procurement process, or when operational with the fleet. The goal of this thesis is to develop naval diesel engine exhaust air emission test procedures.

The cargo variant of the LSD 41 Class of ships is still under construction for the U.S. Navy. This ship class is the most modern diesel ship in the U.S. Navy fleet. It features an automated engine bell recording system, automated diesel trend analysis collection, and has achieved a very high engine reliability rating. For these reasons it was selected for study in this thesis.

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[2]E.B. Potter, NIMITZ, p. 125.

[3]Naval Sea Systems Command, "Internal Combustion Engine Exhaust Emission Study," 1991, p. 7-18.

1.2 LSD 41 Class

The twelve ships of the LSD 41, *WHIDBEY ISLAND,* Class have four medium speed Colt SEMT-Pielstick 16 PC2.5 V400 diesels, each rated at 8,500 brake horsepower for main propulsion. Two diesels are connected by clutch to a mechanical reduction gear which drives the 13.5 foot diameter controllable reversible pitch propellers through a propulsion shaft. The combined 34,000 brake horsepower (33,000 shaft horsepower) propels the two shafts and powers the 15,745 ton ship to a maximum speed of approximately 22 knots. Ships service electrical power is provided by four Fairbanks Morse 38ND8-1/8 opposed piston diesel engine driven 1300 kW electrical generators.

The LSD 41 Class is comprised of eight ships of landing-ship-dock configuration and four cargo carrying variants. The mission of this ship class is to provide amphibious assault capability to 450 troops and four air cushion landing craft. This ship is designed and built to operate within visual range of shore and has been recently deployed in support of United Nations initiatives in Iraq, Somalia, and Haiti.

1.3 Pollutants of Interest

Since the beginning of human of civilization the benifit of increased industrialization has brought with it the price of pollution. In our modern world the internal combustion engine is the workhorse of commerce. As a source of power, its high energy conversion to weight density has made it the engine of choice for powering our automobiles, trucks, aircraft, and ships. With the shift

from wind powered sailing ships, and horse drawn vehicles has come an increase in anthropogenic atmospheric chemicals. These pollutants have degraded the quality of life of our civilization by endangering public health, degrading the public welfare in decreased visibility and by damaging our buildings and natural world.

Like all internal combustion engines, diesel engines intake fresh air, burn a fuel/air mixture, produce work and exhaust gases. Currently, the diesel cycle is the most efficient of the heat engine cycles widely used. However, processes such as incomplete fuel combustion, engine friction, and heat loses all reduce efficiency. The complete stoichiometric combustion of diesel fuel is given by equation (1):

$$C_{10}H_{17}+14.25(O_2+3.77N_2)=10CO_2+8.5H_2O+15.76N_2 \tag{1}$$

Complete stoichiometric combustion is rarely achieved because of nonuniform mixing of air and fuel. Diesel engines are operated with excess air (lean) to enhance the combustion process. Within the cylinder of a typical diesel engine, combustion takes place under different regimes. In those areas where stoichiometric conditions exist, complete combustion occurs. These areas are typified by high temperature leading to oxidation of atmospheric nitrogen and production of nitric oxide (NO) and nitrogen dioxide (NO_2). Oxides of nitrogen (NO_X) are comprised of NO (80-90%) and NO_2 (10-20%).

Surrounding the stoichiometric regions are fuel lean and fuel rich areas.

The fuel lean regions are typified by lower temperatures and complete fuel combustion due to an excess of oxygen and the dilutive effect of excess air. The fuel rich regions have incomplete combustion due to a shortage of oxygen. In these areas carbon monoxide (CO) and pyrolized and unpyrolized fuel hydrocarbons (HC) are produced. Since diesel engines are normally operated fuel lean CO and HC products are not a substantial problem. Carbon dioxide (CO_2) and water (H_2O) are the ultimate products of complete fossil fuel combustion. The rate of CO_2 production increases with combustion efficiency. Optimization of the combustion process leads to an increase in CO_2 production, a gas generally accepted as contributing to global warming by the green house effect.

Normal engine operation encompasses both steady state and transient conditions. Transient conditions occur during acceleration and deceleration between steady state conditions. During transients the fuel-to-air ratio changes, engine responsiveness is limited by the air intake system. The result is fuel rich combustion. Transient conditions are characterized by decreased NO_X and increased CO, HC and PM levels in the exhaust.

Diesel fuel contains a small (1-5%) amount of sulfur which combines with oxygen in the combustion chamber to form sulfur oxides (SO_X). Sulfur oxides have been shown to contribute to acid rain, degrade visibility and increase human respiratory problems. The problem of sulfur is being addressed by the specification for low sulfur fuels.

The State of California has completed several air quality studies. These indicate marine vessels substantially contribute to pollutants in the ambient air inventory. Table 1-1 provides a comparison of marine vessel emissions versus other sources for the state of California in 1987. Contained in the study are emissions from all vessels, including diesel, gas turbine, and steam powered vessels. The vast majority of the approximately 22,500 vessels which operated in California waters during 1987 were diesel powered. Economic pressures forced the conversion of most steam and gas turbine commercial ships to more efficient diesel power during the 1970's and 80's. However, this trend has had a negative impact on ambient air quality as diesel engines produce about 10 times more NO_X than steam boilers.[4] The percent contribution of NO_X and SO_X by marine vessels is primarily due to lack of emission regulation compared to other

Table 1-1: Marine Vessels Versus Other Sources (tons/day)[5]

Source	HC	CO	NO_X	SO_X	PM
Stationary	5,300	6,000	970	210	11,000
On-Road	1,600	11,000	1,900	130	270
Off-Road	341	4,005	789	50	58
Marine Vessels	29	57	412	226	28
Total	7,270	21,062	4,071	616	11,356
% Marine	0.40	0.27	10.1	36.7	0.25

[4]State of California Air Resources Board, "Public Meeting to Consider a Plan for the Control of Emissions from Marine Vessels," p. 2, 1991.

[5]Ibid., p. 9.

more numerous sources, and the high sulfur content of fuels used for commercial diesel powered ships. Marine vessel emissions are further broken down by vessel type (Table 1-2) and location (Table 1-3).

Table 1-2: Marine Vessel Emissions by Vessel Type (% Contribution)[6]

Vessel Type	Number	NO_X	SO_X
Ocean-Going	15,491	74 %	69 %
Harbor	268	2 %	15 %
Commercial Fishing	6,807	24 %	16 %

Table 1-3: Marine Vessel Emissions by Vessel Location (tons /day)[7]

Vessel Location	NO_X	SO_X
In-port	74 (18%)	34 (15%)
At-sea	238 (58%)	155 (69%)
Commercial Fishing	100 (24%)	37 (16%)
Total	412 (100%)	226 (100%)

Marine diesel pollutants of prime importance for future regulation are NO_X and particulate soot (PM) which is comprised of carbon and imbedded hydrocarbons. A relationship has been determined to exist between NO_X and PM. Engine in cylinder design changes to reduce NO_X generally correspond to an increase in PM production. Therefore, diesel engine designers trade off fuel efficiency and reduced NO_X against increased PM. Figure 1 demonstrates that

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[6]Ibid., p. A-3.

[7]Ibid., p. A-2.

the rate of PM emissions trade-off tends to increase exponentially as the NO_X emission level gets lower.[8] The curve of Figure 1 represents the technology average for on-highway heavy-duty engines produced between 1988 and 1990.

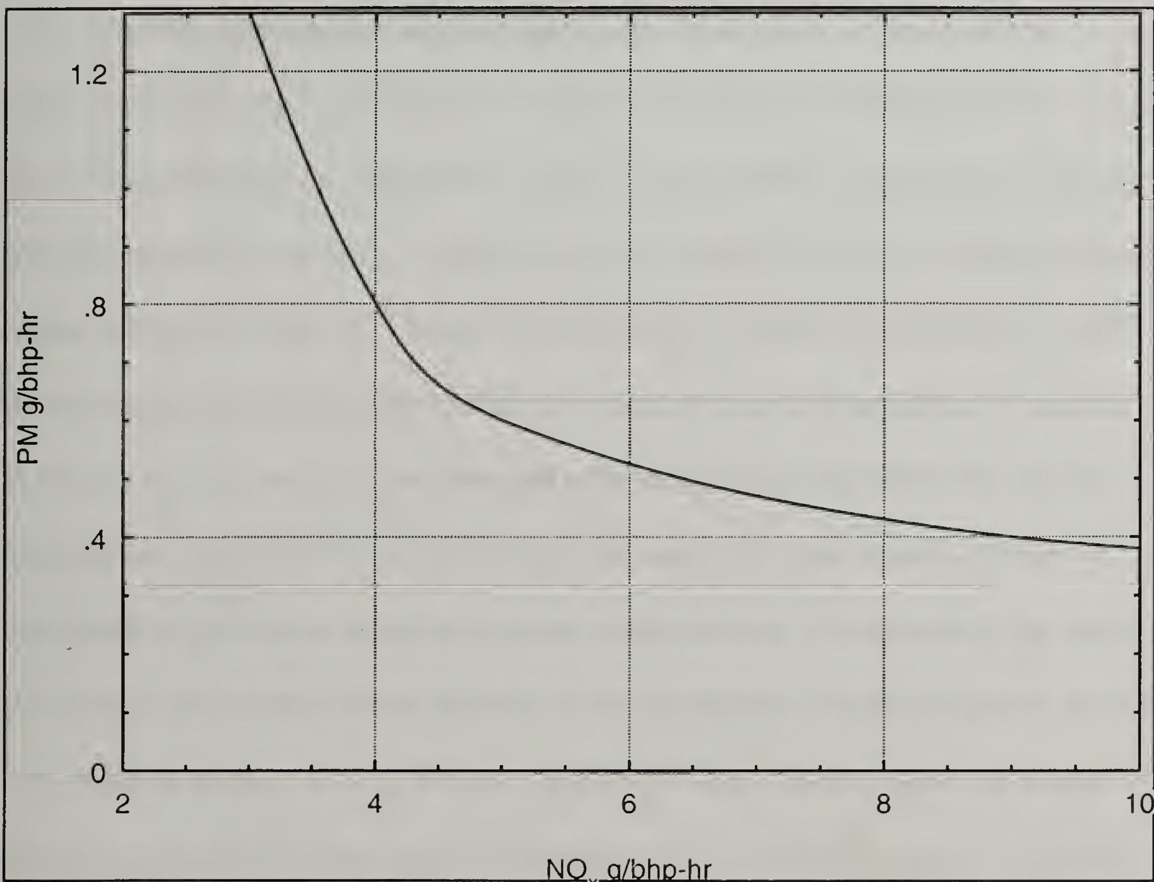

Figure 1: Particulate - NO_X Trade Off

Engine exhaust emissions from ships present a more complex analytic problem than non marine sources. Unlike trucks and locomotives, marine diesel engines are connected to a long exhaust pipe (uptake). The LSD 41 Class has two exhaust stacks, each of which contain the uptakes of two main propulsion

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[8]"Control of Air Pollution: Emissions of Oxides of Nitrogen and Smoke From New Nonroad Compression-Ignition Engines at Above 50 Horsepower," Federal Register, Volume 58, No. 93, 17 May 1993, p. 28836.

and two ship service diesel engines. Within the uptake, gases may continue to react with each other and ambient air, oxidation and reduction processes continue driven by temperature. Therefore, emissions from the engine exhaust valve may be different than what ultimately exits the stack. After treatment schemes such as selective catalytic reduction (SCR) take advantage of exhaust gas stream chemistry to reduce NO_X levels. Since ambient air quality is directly affected by stack emissions, regulatory action should be stack (or uptake) based rather than engine based. However, the diversity of diesel engines and uptake designs would complicate traditional command and control regulation if applied to ships. For this reason, the chemical processes occurring within the uptake must be well understood to equate engine to stack (or uptake) emissions over the spectrum of engine speed and power combinations. Complicating the stack (or uptake) gas measurement scheme is the distribution of exhaust gases across the uptake diameter. The turbulent nature of the gas stream makes prediction of gas levels at distinct locations very difficult due to associated velocity, pressure, and temperature gradients. Continued degradation of urban ambient air quality has resulted in increasingly tougher legislative and regulative initiatives to reduce the emission of diesel generated NO_X , CO, SO_X and PM. Current understanding of uptake gas chemistry does not allow accurate emission prediction at the stack exit. As regulations drive emissions downward, reliance on diesel engine derived emission criteria for procurement and trend analysis coupled with the beneficial effects of mixing and cooling in the uptake, and stack

exit monitoring for certification and compliance will give the U.S. Navy the best means for conforming to emission standards.

1.4 Legislative Initiatives

The International Maritime Organization (IMO) has acknowledged that national and regional legislation to limit engine exhaust emissions from ships is inevitable. In response, the IMO's Marine Environmental Protection Committee (MEPC) is currently working on standards for the prevention of air pollutants from ships. Specifically targeted is the reduction of NO_X and SO_X without an increase in other air pollutants. IMO has agreed to formulate a new annex to the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78. The new annex, Annex 6, will apply to new diesel engines over 100 kilowatts, and to non-public vessels over 500 gross tons. Proposed SO_X reduction of 50 percent of 1992 levels by 2000 is to be accomplished by a global cap of 3-4 percent fuel sulfur content and a limit of fuel sulfur of 1.5 percent on a regional basis in special areas. For new engines, 70 percent reduction of 1992 levels by 2000 for NO_X have been proposed. IMO anticipates completing work on Annex 6 by the end of 1994. Although the U.S. Coast Guard has participated in the development of Annex 6 as the official representative of the U.S. government, ratification by the U.S. Congress would be required to make Annex 6 law. Even though Annex 6 will likely exempt public vessels, it is probable that the U.S. Congress will mandate public vessel compliance upon ratification. Congress did just that when it ratified Annex 5 to MARPOL 73/78 in 1987

requiring public vessels to comply with the commercial standards. Regardless of what occurs in the international arena, control of emissions has been a priority of all levels of government within the United States.

The U.S. Congress enacted the Clean Air Act (CAA) in 1970. The central theme of the CAA is a cooperative federal-state scheme to achieve nationwide acceptable air quality. Section 108 and 109 of CAA require the Administrator of the Environmental Protection Agency (EPA) to establish national ambient air quality standards (NAAQS) for criteria pollutants. The six primary and secondary NAAQS that have been designated by the Administrator appear in Table 1-4. Primary standards are set to protect the public health with an adequate margin of safety. Secondary standards have been established to protect the public welfare from any known or anticipated adverse effect associated with the presence of such air pollutant in the ambient air.

Section 110 of CAA requires each state to develop State Implementation Plans (SIP's) to achieve the federally mandated primary and secondary NAAQS. In SIP development a state must include enforceable emission limitations and other control measures. The amendments of 1990 added the requirement for states with areas not in attainment to establish vehicle monitoring programs to ensure continued compliance with tailpipe standards.

The CAA in section 202 established emission standards for new motor vehicles or new motor vehicle engines. Specific on-road standards for light duty vehicles and light duty trucks for CO, HC and NO_X were specified in the act.

Table 1-4: National Ambient Air Quality Standards

Criteria Pollutant	Primary Standard	Secondary Standard
Carbon Monoxide (CO)	35 ppm averaged over 1 hour and 9.0 ppm averaged over 8 hours.	None.
Particulate Matter (PM_{10})	150 μg/m^3 averaged over 24 hours, once per year, and 59 μg/m^3 or less annual arithmetic mean.	Same as primary.
Lead (Pb)	1.5 μg/m^3 arithmetic average over a calendar quarter.	Same as Primary.
Nitrogen Dioxide (NO_2)	100 μg/m^3 as annual arithmetic mean.	Same as Primary.
Ozone (O_3)	235 μg/m^3 averaged over 1 hour, one exceedance per year.	Same as Primary
Sulfur Oxides (SO_X)	365 μg/m^3 average over 24 hour period, one exceedance per year; 80 μg/m^3 annual arithmetic mean.	1,300 μg/m^3 average over a 3-hour period, one exceedance per year.

Section 213 of the act tasked the administrator to conduct a study of emissions from nonroad engines and nonroad vehicles to determine if such emissions cause, or significantly contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare. Further, this section required the administrator to issue emission standards for the nonroad source if it is found to endanger public health or welfare. Section 209(e)(2)(A) authorizes the state of California to adopt and enforce standards and other requirements relating to the control of emissions from nonroad engines or

vehicles not covered elsewhere in the act. Marine vessels and engines are subject to regulation under this section.

The State of California Legislature enacted the California Clean Air Act (CCAA) in 1988 to fulfill its unique status under the federal CAA to pioneer air quality improvement initiatives. Under this act, the California Air Resources Board (CARB) was required to consider controlling emissions from several previously unregulated nonroad mobile sources. Marine vessels and engines were included in the act for CARB regulation. CARB has proposed regulation of vessels operating within a zone defined as "California Coastal Waters". This area parallels the California coast and is within 27 miles off Point Conception, and as far as 100 miles off the San Francisco Bay Area. The distances were developed based on meteorological and modeling data showing emissions off the coast affect coastal land areas. Information supplied to CARB by the U.S. Coast Guard indicates all commercial shipping calling at California Ports transits within 20 miles of shore. The U.S. Navy conducts extensive amphibious assault training exercises off the coast of the Camp Pendelton Marine Base in San Diego County, an area within the coastal waters zone. Figure 1 gives a chart of the designated California Coastal Waters. Figure 1 was taken from page 12 of the report commissioned by CARB entitled "Regulatory Strategies for Reducing Emissions from Marine Vessels in California Waters," which was prepared by Sierra Research on 4 October 1991. Also depicted in Figure 1 are the California coastal air management districts (AQMD's).

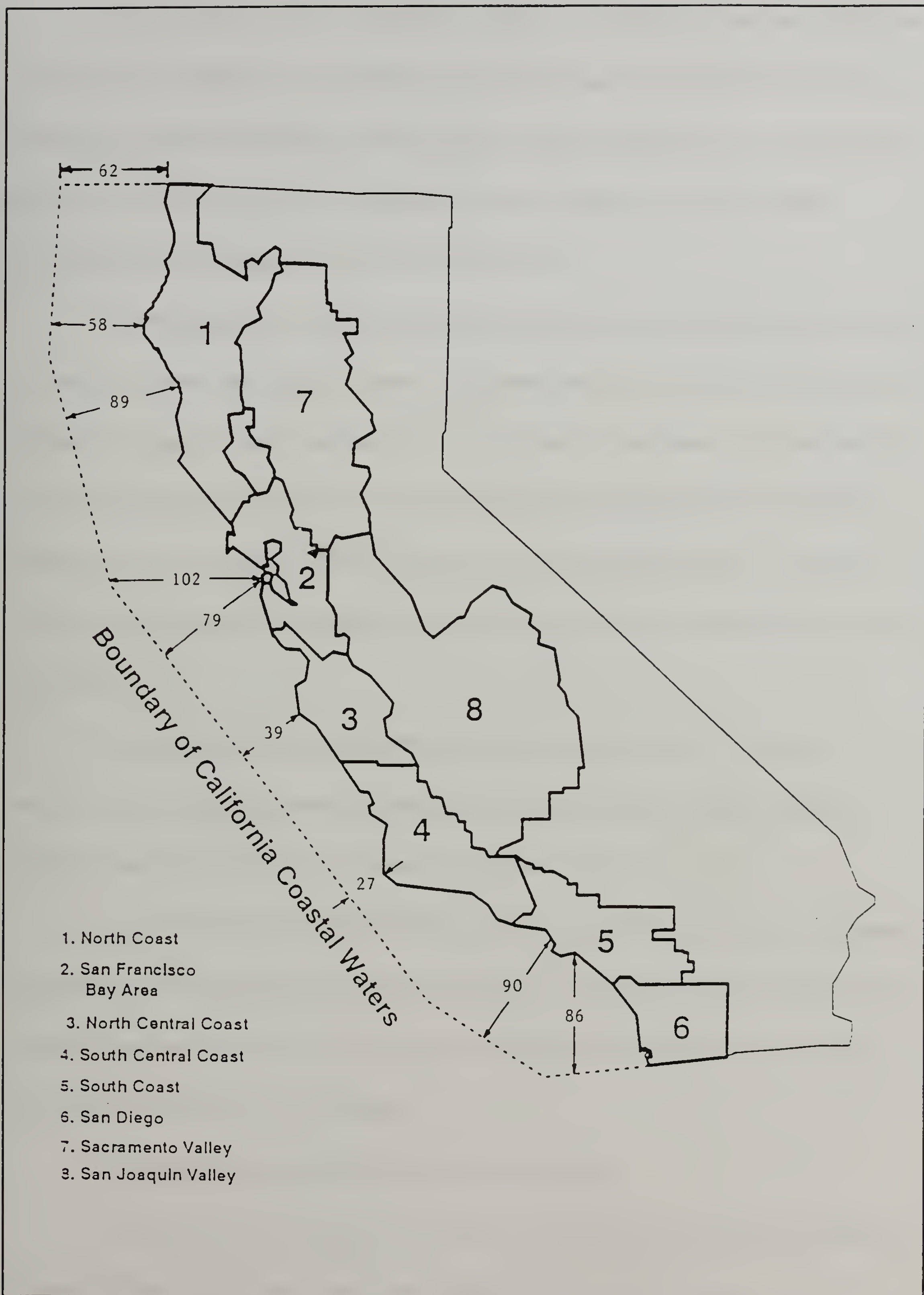

Figure 2: California Coastal Water Air Basins - Distances in Miles

On 24 February 1994, the Administrator of the EPA signed the California Federal Implementation Plan (CFIP). The CFIP was developed by EPA since California had not developed SIP's for each of their AQMD's as it was required to do under CAA. The CFIP maintains the basic elements of the CARB proposed plan and adds an emission fee system.

The fee system proposed in the CFIP significantly impacts frequent users of California ports and high emitters. The basic fee of $10,000 per U.S. ton NO_X emitted will apply to commercial shipping. Table 1-1 indicates that commercial ships operating in the California Coastal Waters zone emit 412 tons/day NO_X. At this emission rate, $4,120,000 in fees would be collected daily. Incentives within the fee collection system reward reductions in NO_X. These incentives are as follows:

- 90 percent fee reduction for 80 percent NO_X reduction. Possible methods for accomplishment are through use of selective catalytic reduction (SCR) or shift to gas turbine or diesel propulsion plants.

- 50 percent fee reduction for 30 to 80 percent NO_X reduction. Suggested alternatives for acomplishement are: injection timing retard, engine fine tuning, exhaust gas recirculation (EGR), water emulsification, selective non-catalytic reduction, and reduced ship speed.

- Full fee if less than 30 percent NO_X reduction.

- Fee reduction for use of the relocated Santa Barbara shipping channel (located farther out to sea), and use of shore power when in port.

The fee system is expected to encourage the development of shipboard emission control systems and provide incentives for more efficient operation and use of shore power inport (cold-ironing). Each commercial vessel operating in California coastal waters must report hours of operation and rated power for each engine on board.

Four basic assumptions have been made in developing the fee model:

1. Cruising: 3 - 100 miles from port. Assume 80 percent of rated engine output

2. Maneuvering/Hotelling: <3 miles from port. Assume 25 percent rated output.

3. Auxiliary Engines: Assume 50 percent rated engine output.

4. Baseline emissions from main engines determined from modified engine speed emission model from Japan. This model equates NO_X to RPM and is based upon engine research conducted in Scandinavia and Japan. Figure 3 illustrates this relation.[9]

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[9]Larry N. Hottenstein, "International Impact of California's Engine Emissions Regulations," presentation to ASNE Maritime Environmental Symposium '94, 23 February 1994.

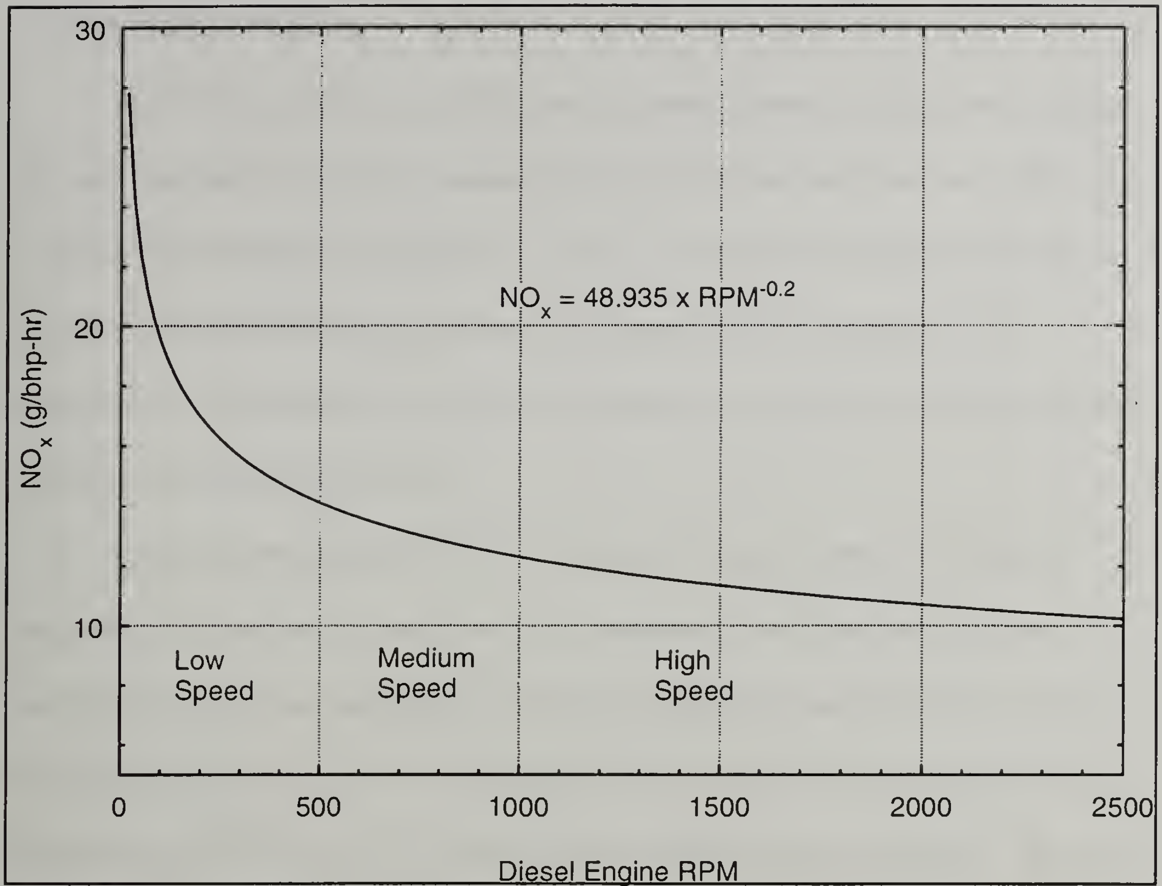

Figure 3: Japanese NO_x Formula

The CFIP presents a clear shift in regulatory strategy. The impact of its full implementation on the work of the IMO and international trade has not been fully assessed. The reliance upon a model equating NO_x to RPM without regard for engine torque or cylinder pressures indicates that the regulatory environment is shifting from analysis to action, but not necessarily the prudent action.

1.5 Regulatory Strategy

The U.S. Congress and EPA have adopted a pareto regulation strategy. To date standards have been established for stationary sources, and light-duty vehicles (automobiles and light-duty trucks). This practice regulates those air pollution sources where the greatest cost/benefit ratio can be had. The emphasis for new regulation in the 1990's will be for the more numerous smaller stationary and mobile sources.

The EPA has broad authority to study, propose, enact, and enforce regulations of mobile nonroad emission sources. The Administrator has periodically published emission controls for heavy duty diesel engines under transient conditions, Table 1-5. Although not binding on marine vessels, these standards offer a preview of probable future marine diesel standards. The trend seen in Figure 4 illustrates the gradual decrease in allowable emissions. EPA has universally defined heavy-duty diesel engines as those installed in a vehicle/vessel of over 33,000 pounds gross vehicle weight.[10] This definition applies to the propulsion and auxiliary engines of large trucks, earth moving equipment, locomotives, and marine vessels. Interestingly, the EPA has adopted a vehicle derived engine classification, instead of one based on horsepower, useful life, etc...

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[10]PHONECON with Mr. John Roach, EPA Air Quality Division, Boston, MA, of 17 November 1993.

Table 1-5: EPA Heavy-Duty Diesel Emission Standards (g/bhp-hr)

Year	NO_X	PM
1986	10.7	0.60
1990	6.0	0.60
1991	5.0	0.25
1994	5.0	0.10
1998	4.0	0.10
2000*	2.5	0.05

Note: * CARB proposal.

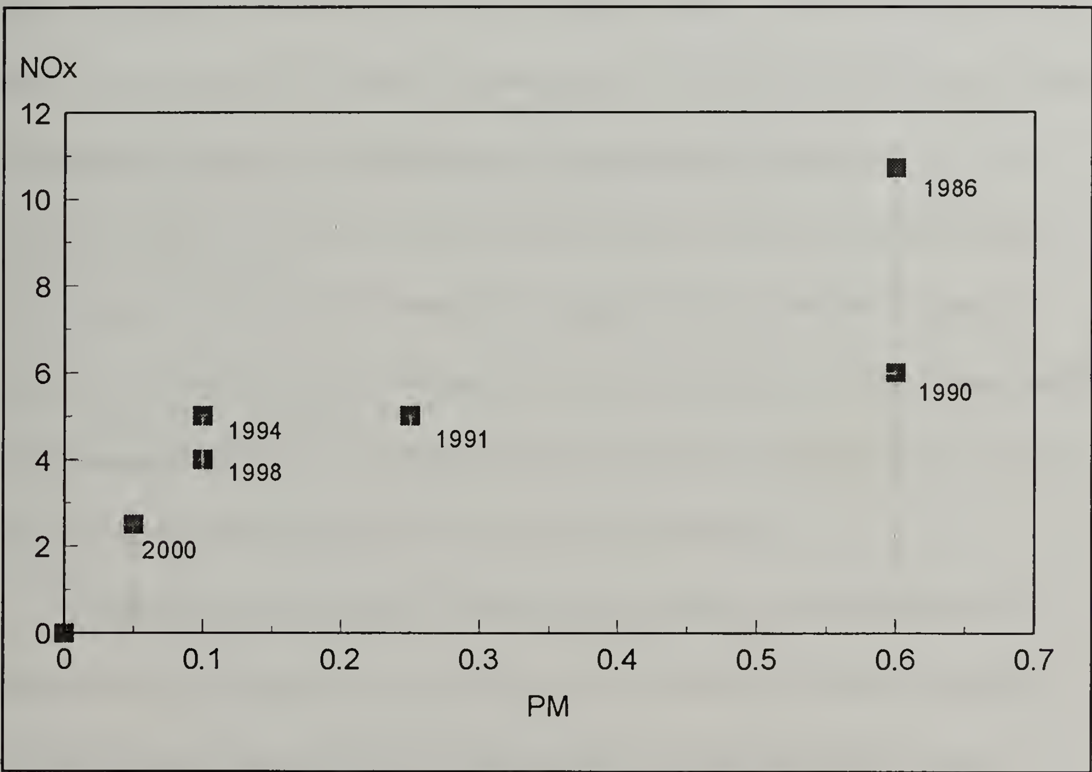

Figure 4: NO_X and PM Heavy Duty Engine Standards

The EPA completed its study of nonroad engine and vehicle emissions in November 1991. Based on this study, on 17 May 1993 EPA proposed nonroad

heavy duty diesel emission standards of 6.9 g/bhp-hr NO_X and proposed smoke opacity standard of 20% during acceleration, 15% on lug mode, and 50% peak opacity on either the acceleration or lug mode. EPA did not issue proposed emission standards for HC, CO and PM. Available test procedures had not been demonstrated capable of predicting these pollutant emissions from nonroad sources. Specifically excluded from these proposed regulations are engines used for main propulsion and auxiliary power in marine vessels. Marine vessel engines were not included for two reasons. First, marine engines are currently subject to safety regulations by the U.S. Coast Guard. EPA must first analyze these current Coast Guard safety requirements, then determine the best method for regulating emissions, consistent with Coast Guard regulations. Second, information was unavailable verifying existing test procedures as applicable to marine engines. EPA must determine a suitable test procedure for marine vessels. Although U.S. Navy vessels are not subject to U.S. Coast Guard safety regulations, the EPA has recognized that existing test procedures may not be adequate for predicting marine diesel engine emissions.[11]

Regardless of EPA action, CARB has proposed new marine vessel engine emission standards, in-use marine vessel engine emission standards, new and existing source permit requirements, and a broad market based strategy aimed at reducing vessel exhaust emissions effective in 1995. Table 1-6 provides these new proposed NO_X standards applicable to marine diesel

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[11]Federal Register, Vol. 58, No. 93, p. 28816.

engines.

Effective 01 October 1993 highway diesel fuel must comply with a maximum sulfur content standard of 0.05 percent by weight. California has extended the EPA low sulfur requirement to include fuel sold for marine applications. The sulfur problem should be substantially resolved by specification for low sulfur fuel.

Table 1-6: CARB 1995 Marine Vessel Proposed Diesel NO_X Emission Standards (ppm)[12]

Application	Load	Baseline	Proposed	% Reduction
New Engines				
Main Propulsion	≥ 25%	650-1,200	130	78-89
Main Propulsion	< 25%	*	450	*
Auxiliaries	*	600-1,200	600	0-50
Existing Engines				
Main Propulsion	*	600-1,680	600	0-64
Auxiliaries	*	650-1,200	750	0-38

The development of a marine test procedure is vital for providing repeatable emission data. Several duty cycles have been proposed to accomplish this. However, the unique operation of U.S. Naval ships has not yet been properly modeled.

1.6 Diesel Engine Duty Cycles

Regardless of the regulatory strategy adopted by federal or state

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[12]State of California, p. 13.

governments, the relationship between the operation of marine vessels and ambient air quality must be understood. Section 206 of the CAA requires the administrator of the EPA to test new engines for compliance with existing emission standards. Although marine engines are not currently regulated by EPA, duty cycles have been developed for marine vessels and are being evaluated for EPA certification.

Certified duty cycles have been developed for both highway and nonroad applications. These tests provide repeatability, wide applicability, and simplicity in modeling engine operating profiles. There are two distinct types of duty cycles; constant volume sampling (CVS) used for transient testing, and mode testing used for steady state. The CVS test uses a bag collection device. Mode testing relies upon raw gas stream measurement.

The contribution of transient operation to total emission levels is currently being investigated. Information to date suggests that transients may not be critical in most emission measurement schemes. EPA analysis of their own and industry test data during normal engine operation has shown that NO_X emission levels remain relatively consistent over a range of steady state to transient operation.[13] In developing a duty cycle for recreational marine engines, the International Council of Marine Industry Associations (ICOMIA) provided evidence that transient operation encompasses only a small fraction (1-2%) of total operating time. This was interpreted as a result of a small number of

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[13]Federal Register, Volume 58, No. 93, p. 28820.

throttle changes.[14] The data analyzed for this thesis agrees with the ICOMIA data. One is led to the conclusion that understanding steady-state conditions is far more important than transient conditions in duty cycle development and testing.

Acceleration transient testing conducted on the U.S. Coast Guard Cutter *POINT TURNER* in the fall of 1993, indicated that maximum NO_X and CO levels are not that much different than the steady state condition at the higher power level. In this testing the engines were accelerated from the clutched mode (180 shaft rpm, 5 horsepower), to 650 shaft rpm and roughly 580 horsepower. During the transient, NO_X, as measured in ppm_V at 1 second intervals with a ENERAC model 2000E Portable Emissions Analyzer, was found to first decrease substantially before building up to the steady state value. CO was found to first increase at a fast rate, then gradually to attain the steady state value. The results observed are consistent with transition from steady state while clutched, to fuel rich during the first part of acceleration, and restoration of the steady state fuel/air ratio at the end of the transient event.

The results of emission testing may be reported either as a maximum single-point or as a weighted average over an operating profile. Maximum single-point measurements indicate worse case operation. This point may be measured outside of the normal operating range of the engine tested. The

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[14]Edward J. Morgan, "Duty Cycle for Recreational Marine Engines," SAE Paper No. 901596, 1990, p. 10.

proposed marine emission levels described in Table 1-6 are of the maximum single-point type. These levels are reported based on volumetric flow rate (ppm_V), maximum brake specific mass level, or as the emission index given in grams per kilogram of fuel. The weighted average method tests the engine over a profile of varying loads and speeds. This method obtains a more accurate estimation of engine emissions as a function of power produced (g/bhp-hr). An accurate engine operating profile is required for the weighted average method. The weighted average method is preferred since it provides an indication of emissions over the actual operating range of the engine.

Several duty cycles have been proposed for marine vessels. Each duty cycle specifies speed/power combinations with factors indicating time percentage at that combination. Duty cycles are classified as Ψ-Mode; Ψ indicates the number of combinations tested. Duty cycles with a greater number of combinations (Ψ) provide greater emission/efficiency detail. However, the selection of speed/power and time in mode must be done carefully so as to accurately reflect actual operation. If poorly performed, data will not be representative of actual operating conditions.

1.6.1 DEMA Duty Cycle

The predecessor of the Engine Manufactures Association (EMA), the Diesel Engine Manufactures Association (DEMA), published a 3 mode duty cycle in 1974. Although no longer supported by EMA, the duty cycle provided an early attempt to model a generator engine operating profile. This duty cycle assumes

constant speed operation and is provided in Table 1-7.

Table 1-7: DEMA Duty Cycle[15]

Cycle Point	Specified Load, %	Time Factor
1	50	0.2
2	75	0.4
3	100	0.4

1.6.2 ICOMIA Standard No. 36-88

ICOMIA Standard Number 36-88, Marine Engine Duty Cycle, provides a 5-mode duty cycle for recreational and commercial marine engines. Table 1-8 gives this duty cycle. This cycle emphasizes low speed/torque operation which may be applicable to U.S. Navy ships maneuvering in a harbor or when conducting on-station duties just over the horizon from shore.

Table 1-8: ICOMIA Marine Engine Duty Cycle (Standard No. 36-88)[16]

Mode	Engine Speed*	Engine Torque*	Time Factor
1	Idle	0	0.40
2	0.4	0.253	0.25
3	0.6	0.465	0.15
4	0.8	0.716	0.14
5	1.00	1.000	0.06

Note: * As a fraction of engine rating.

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[15]Naval Sea System Command, 1991, p. 6-10.

[16]Edward J. Morgan and Richard H. Lincoln, "Duty Cycle for Recreational Marine Engines", SAE Paper 901596, 1990, Appendix 2.

1.6.3 EPA 13-Mode Duty Cycle

The 13-Mode EPA Duty Cycle has been used for several years for standardized steady state heavy-duty diesel engine emission testing. Table 1-9 gives the EPA 13-Mode Duty Cycle.

Table 1-9: EPA 13-Mode Duty Cycle[17]

Mode	Engine Speed	Engine Torque*	Time in Mode		Time Factor
			Min.	Max.	
1	Idle	0	4.5	6	0.067
2	Intermediate	2	4.5	6	0.08
3	Intermediate	25	4.5	6	0.08
4	Intermediate	50	4.5	6	0.08
5	Intermediate	75	4.5	6	0.08
6	Intermediate	100	4.5	6	0.08
7	Idle	0	4.5	6	0.067
8	Rated	100	4.5	6	0.08
9	Rated	75	4.5	6	0.08
10	Rated	50	4.5	6	0.08
11	Rated	25	4.5	6	0.08
12	Rated	2	4.5	6	0.08
13	Idle	0	4.5	6	0.067

Note: *Percent of Maximum Observed

The EMA and Economic Commission for Europe (ECE) have proposed alternatives to the weighting (time) factors for the standard U.S. EPA 13-Mode

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[17] Ibid., p. 6-7.

Duty Cycle for nonroad applications. Table 1-10 provides this comparison.

Table 1-10: Nonroad Weighting Factors v. EPA 13-Mode Duty Cycle[18]

Mode	Time Factors (%)		
	U.S. EPA	ECE 49	EMA
1	20/3	25/3	15
2	8	8 (10 % Load)	0
3	8	8	0
4	8	8	10
5	8	8	10
6	8	0	10
7	20/3	25/2	0
8	8	8	15
9	8	8	15
10	8	8	15
11	8	8	0
12	8	8 (10% Load)	10 (10% Load)
13	20/3	25/3	0

1.6.4 Japanese Heavy-Duty Diesel Duty Cycle

Japan has established itself as a major contributor in heavy-duty diesel engine research and development. They have developed a six mode duty cycle for engine testing, Table 1-11. This duty cycle emphasizes higher engine speed and heavier loading conditions than the standard EPA 13-Mode. It does not test full load at rated speed.

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[18]Ibid. p. 6-12.

Table 1-11: Japanese Heavy-Duty Diesel Duty Cycle[19]

Mode	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor (%)
1	Idle	0	3.5
2	40 or 1000 rpm	100	7.1
3	40 or 1000 rpm	25	5.9
4	60	100	10.7
5	60	25	12.2
6	80	75	28.6

1.6.5 U.S. Navy Endurance Test

The U.S. Navy procures medium speed heavy-duty diesels subsequent to successful completion of the 1,000 hour endurance test, comprised of 125 eight hour cycles. Although emission measurements are not taken concurrent with this test, steady state readings could be made. The data would not reflect inservice emission levels unless the durability test were modified to conform to the individual ship application operating profile. Table 1-12 gives the U.S. Navy durability test cycle (8 hour).

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[19] Ibid., p. 6-13.

Table 1-12: U.S. Navy Medium Speed Diesel Engine Endurance Test[20]

Mode	Time (minutes)	Time Factor	Engine Load (% of Rated)	Engine Speed (% of Rated)
1	120	0.250	100	100
2	60	0.125	85	100
3	10	0.021	0	Idle
4	110	0.229	100	100
5	10	0.021	0	Idle
6*	30	0.063	50	75 (Reverse)
7	10	0.021	0	Idle
8	10	0.021	85	100
9	110	0.229	110	100
10	10	0.021	0	Shutdown

Note: *For main propulsion engines, for constant speed engines (SSDG) 50% load at rated speed in the forward direction.

1.6.6 ISO 8178-4 Duty Cycles

The International Organization for Standardization (ISO) published its draft proposal "Reciprocating Internal Combustion (RIC) Engines - Exhaust Emission Measurement", ISO 8178, in May of 1992. ISO 8178 is a five part procedure designed to standardize engine exhaust measurement. Part four provides 13 duty cycles for different engine applications. The EPA is currently evaluating ISO 8178 for use in the United States. Table 1-13 gives the 13 duty cycles, and Table 1-14 defines them.

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[20]Military Specification, "Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed," MIL-E-23457B, March 1976, p. 23.

Table 13: ISO 8178-4 RIC Duty Cycles[21]

TEST	Idle	60 Percent of Rated Speed					Rated Speed				
	Percent Load										
	0	10	25	50	75	100	10	25	50	75	100
A	0.25	0.08	0.08	0.08	0.08	0.25	0.02	0.02	0.02	0.02	0.10
B	0.25	0.08	0.08	0.08	0.08	0.25	0.02	0.02	0.02	0.02	0.10
C1	0.15	*	*	0.10	0.10	0.10	0.10	*	0.15	0.15	0.15
C2	0.25	*	0.30	*	*	0.07	0.23	*	*	*	0.07
D1	*	*	*	*	*	*	*	*	0.20	0.50	0.30
D2	*	*	*	*	*	*	0.10	0.30	0.30	0.25	0.05
F	0.60	*	*	0.15	*	*	*	*	*	*	0.25
G1	0.05	0.07	0.30	0.25	0.20	0.09	*	*	*	*	*
G2	*	*	*	*	*	*	0.07	0.30	0.29	0.20	0.09
G3	0.10	*	*	*	*	*	*	*	*	*	0.90
E1	0.40	*	0.25	0.15	0.14	*	*	*	*	*	0.06
E2	*	*	*	*	*	*	*	0.15	0.15	0.5	0.2
E3	% Speed/ % Load/ Weight			63/25/0.15		80/50/0.15		91/75/0.50		100/100/ 0.20	

The series E duty cycles have been proposed for marine application. Cycles E2 and E3 are applicable to U.S. Navy ships with diesel main propulsion engines. Both are four mode tests that do not adequately cover the light loading condition common to near land operation. Cycle D1, a three mode duty cycle, applicable to power generation plants, does not cover the low load ranges that

[21]ISO 8178-4, and Naval Sea Systems Command, p. 6-15.

Table 1-14: ISO 8178 Duty Cycle Definitions

Cycle	Description
A	Reference cycle for vehicle engines.
B	Universal cycle, applications similar to on-road vehicle service.
C1	Off-road vehicles and industrial equipment, medium and high load.
C2	Off-road vehicles and industrial equipment, low load.
D1	Constant speed applications, power plants.
D2	Constant speed applications, generator sets with intermittent load.
E1	Marine engine applications, pleasure craft engines.
E2	Marine engine applications, constant-speed engines for ship propulsion.
E3	Marine engine applications, heavy-duty propulsion engines.
F	Locomotive applications.
C1	Small engines, utility lawn and garden.
G2	Small engines, utility lawn and garden.
G3	Small engines, handheld equipment.

typify shipboard SSDG lineups for maximum redundancy/reliability. ISO 8178 has attempted to cover the entire spectrum of RIC engines in use throughout the world. However, what may be applicable for commercial shipping is not valid for military vessels. Therefore, a need exists for additional duty cycles that provide a reliable naval warship operating profile.

1.6.7 CARB 8-Mode Duty Cycle

In 1990 CARB introduced an eight-mode duty cycle that measured engine emissions under high loading conditions. Each mode of the CARB cycle was held for three minutes of steady operation and sufficient time was allowed

between points to stabilize the next condition. This duty cycle provided a good indication of engine emissions under steady state and high load conditions. Table 1-15 gives the CARB duty cycle.

Table 1-15: CARB 8-Mode Duty Cycle[22]

Mode	Engine Speed	Engine Load (% of Rated)	Time Factor
1	Idle	0.00	0.05
2	Rated	0.75	0.15
3	Rated	0.50	0.15
4	Idle	0.00	0.05
5	Max. Torque	1.00	0.15
6	Max. Torque	0.75	0.15
7	Max. Torque	0.50	0.15
8	Max. Torque	0.30	0.15

The time factors listed in Table 1-15 are esitmates based upon the ISO 8178-4 C1 Duty Cycle which superceded the CARB 8-Mode Duty Cycle. The CARB time factors were not available for inclusion in this thesis. CARB is in the process of evaluating the ISO 8178-4 Duty Cycles for adoption into the CARB program. Evaluation is expected to be completed in 1995 with rule making expected shortly thereafter.

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[22]Paul Stiglic, et. al., "Emission Testing of Two Heavy Duty Diesel Engines Equipped with Exhaust Aftertreatment," SAE Paper 900919, 1990, p. 5.

1.7 Thesis Methodology and Scope

This thesis developed alternative diesel engine duty cycles for naval ships based upon the LSD 41 Class. Duty cycles were devised for both main propulsion engines and ship service diesel generator engines. Of the eight landing-ship-dock variant ships of the LSD 41 Class currently in commission, four were visited for the purpose of log review. Appendix B gives the details of the ship visits conducted for data collection.

Each ship maintains Deck Logs (general ship operation), Engineering Smooth Logs (engineering plant general operation), Engineering Bell Logs (speed change), and Diesel Engine Operating Logs for up to three years. From the information contained in these logs, a ship operating profile was developed. Together with the operating profile, additional information in the form of meteorological, tidal, hull powering requirements, operator preference, scheduled maintenance, inspection reports, and ship specifications was synthesized to generate the two naval diesel duty cycles. Once the duty cycles were written, comparisons were made using data available in the literature describing diesel engine exhaust emissions as a function of speed and power.

After completing the duty cycle portion of this thesis, a study was performed resulting in a recommended stack emission testing methodology. In this work, the ambiguities resulting from turbulent gas flow were accounted for by engineering approximations and modeling.

CHAPTER 2: LSD 41 CLASS OPERATING PROFILE DEVELOPMENT

2.1 LSD 41 Class Description

2.1.1 Hull Naval Architecture Description

The LSD 41 Class design is based on the earlier *ANCHORAGE* Class (LSD 36) of ships. Figure 5 is a port bow view of the *USS WHIDBEY ISLAND* (LSD 41) at sea. Figure 6 provides the LSD 41 Class body plan, which consists of two half transverse elevations or end views of the ship; both have a common

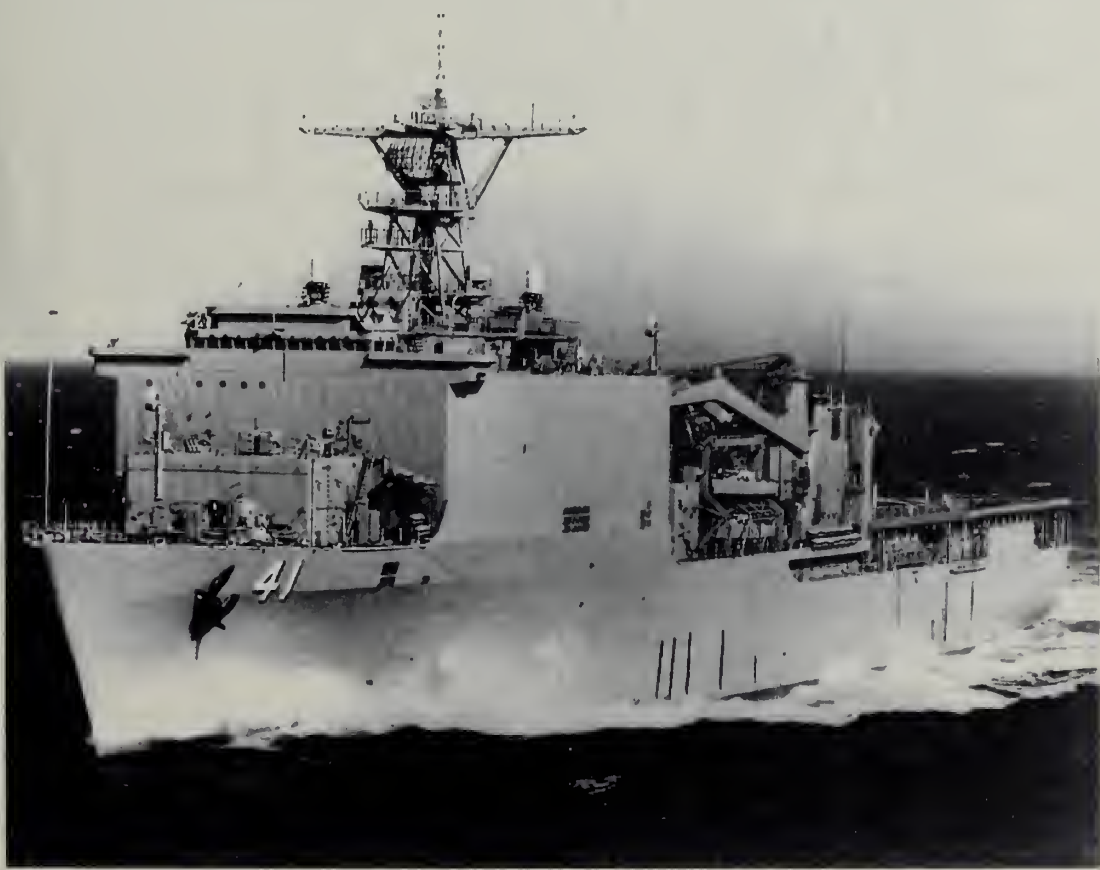

Figure 5: *USS WHIDBEY ISLAND (LSD 41)*

vertical centerline. The right-hand side of Figure 6 represents the ship as seen

from ahead, the left-hand side as seen from the stern. The body plan indicates the cross sectional shape of the ship. This shape directly impacts wetted surface area and, therefore, ship powering requirements. Principle dimensions of the LSD 41 Class are provided in Table 2-1.

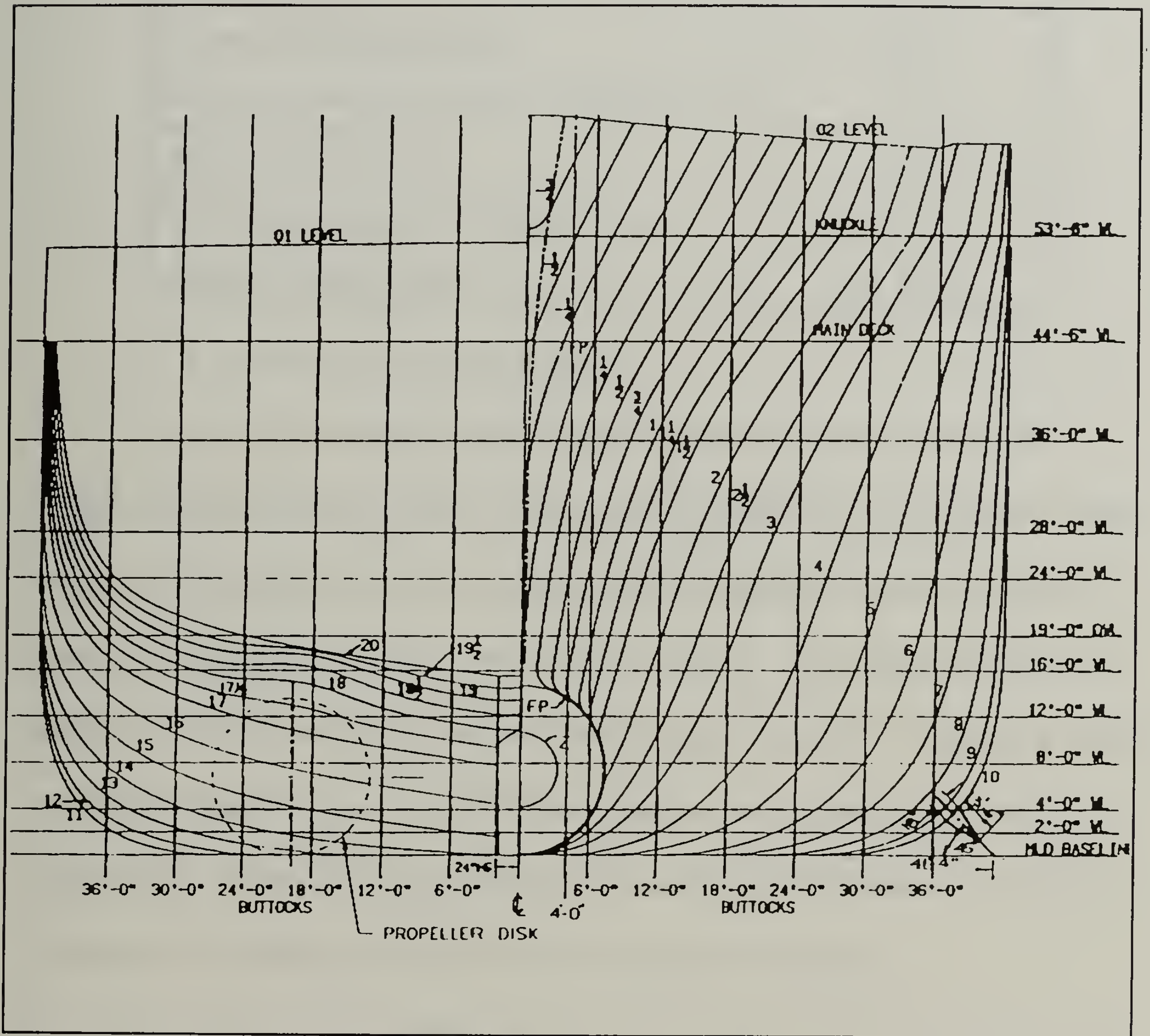

Figure 6: LSD 41 Class Body Plan

Table 2-1: LSD 41 Class Principle Hull Dimensions

Design Displacement	15,745 ltons
Length Overall	609.58 ft
Length Between Perpendiculars	580 ft
Extreme Beam	84 ft
Design Draft	19 ft
Prismatic Coefficient (C_P)	0.612
Maximum Midship Section Coefficient (C_X)	0.945
Block Coefficient (C_B)	0.578
Waterplane Area Coefficient (C_{WP})	0.779
Wetted Surface Area	50,100 ft^2

2.1.2 Propulsion Plant Description

The LSD Class has two shafts. Each shaft is powered by two Colt-Pielstick 16PC2.5V four stroke, turbocharged, intercooled, non-reversing diesel engines. Each diesel must be connected to the Philadelphia Gear reduction gear via pneumatic clutch in order to transmit power. The reduction gear is a locked train single reduction gear with two drive pinions, each clutched to a main propulsion diesel engine. The reduction gear reduction ratio (Λ) is given by equation (2). Power is transmitted into the water via twin 5-bladed, 13.5 foot diameter Bird-Johnson controllable-reversible pitch propellers.

$$\Lambda = \frac{RPM_{Diesel}}{RPM_{Shaft}} = 3.1515 \qquad (2)$$

The Colt Pielstick 16PC2.5V design output is 10,400 brake horsepower (bhp) at air inlet temperature of 51^{O} Celsius. As part of the naval qualification

process diesel engines must produce rated power over a wide temperature range. U.S. Navy specifications call for an operating temperature range of -84° to 60° Celsius. Qualification for U.S. Navy shipboard application required derating the engine by 18% to 8,500 bhp at 520 revolutions per minute (RPM). The shaft torque limits of 262,000 ft-lbs for single engine, and 525,000 ft-lbs for dual engine operation are not exceeded at rated engine operation. The ship is torque limited since at rated RPM rated power is not achieved. To achieve rated power, propeller pitch is adjusted to approximately 70 percent pitch. Basic engine parameters are given in Table 2-2.

Power is lost due to component friction where power is transmitted from the prime mover to the propeller. Mechanical efficiency (η_{MECH}) is the relation between shaft horsepower (shp) measured at the propeller and brake horsepower measured at the prime mover output shaft. Equation (3) provides this relation for the LSD 41 Class.

$$\eta_{MECH}=\frac{SHP}{BHP}=\frac{33,000}{34,000}=0.971 \qquad (3)$$

Table 2-2: Main Propulsion Diesel Engine Parameters

Model	Colt-Pielstick, PC V
Type	Non-Reversing
Cycle	Four Cycle, Turbocharged
Rated Load	8,500 BHP
Rated RPM	520
Minimum Engine Idle	200 RPM
Bore and Stroke - mm	400 x 460
Number of Cylinders	16
Piston Displacement	57.8 Liters
Combustion Chamber Volume	5.51 Liters
Compression Ratio	11.5:1
Equivalence Ratio @ Rated	0.38
bmep @ Rated Conditions	1,934.7 kPa
Piston Speed @ Rated RPM	7.98 m/sec

2.1.3 Ship Service Diesel Generator Description

Ship service electrical power is provided by four 1,300 kW generators, each driven by a Fairbanks Morse 38ND8-1/8 opposed piston diesel engine. These engines are constant speed of 720 RPM. Basic ship service diesel engine parameters are given in Table 2-3.

When underway the ship electric plant is in a parallel configuration, normally with two diesel generators running. Nominal underway ships electric load is approximately 1,300 kW at 1,500 amps. The average load on each machine, with two engines running, gives a load of about 50 percent of rated capacity. Operation of cranes, anchor windlass, and ballast compressor motors

often requires starting an additional diesel generator to provide starting surge capacity. Starting surges are significant, the highest surges are those of the ballast air compressors at 400 amps. Low loading causes glazing of the cylinder liners and build up of carbon deposits. As a result, the diesel prime movers are maintenance intensive.

Table 2-3: Ship Service Diesel Engine Parameters

Model	Fairbanks Morse 38ND8-1/8
Type	Opposed Piston
Cycle	Two Cycle, Turbocharged
Engine Rated Load	1,837 BHP (@ 0.8 p.f.)
Rated Generator Capacity	1,300 kW
Rated RPM	720
Minimum Engine Idle	525 RPM
Bore and Stroke - mm	206.4 x 254
Number of Cylinders	12
Piston Displacement	17.0 Liters
Compression Ratio	16.1:1
Equivalence Ratio @ Rated	0.35
bmep @ Rated Conditions	559.9 kPa
Piston Speed @ Rated RPM	6.10 m/sec

2.2 Ship Powering

The ship propulsion plant must provide sufficient power to overcome the resistance to forward motion. This resistance, or drag, is composed of two primary flow mechanisms; frictional resistance and residuary resistance. Frictional resistance is the largest single contributor to total ship resistance. Experiments have shown it accounts for 80 to 85 percent of total resistance in slow-speed ships and 50 percent in high-speed ships.[23] Air resistance created by the above water portion of the ship also creates drag. Environmental effects in the form of wind, waves, currents, biologic fouling of the hull, and corrosion of the hull magnify the effect of frictional resistance, increasing the power required for a given speed.

Residuary resistance is made up of wave making resistance and eddy resistance. As a ship moves through the water a surface wave system is created. The energy expended by the ship in producing this wave system is called wave making resistance. Eddy resistance refers to the energy that is lost as vortices are produced and shed from appendages such as: propeller shafts, shaft struts, rudders, and ship stern.

At slow ship speeds frictional resistance predominates. At higher speeds the effect of residuary resistance becomes most important. Frictional resistance and residuary resistance are additive. For speed-to-length ratios of less than

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[23]Principles of Naval Architecture Volume II - Resistance, Propulsion and Vibration, SNAME 1988, p. 7.

about 0.6, frictional resistance is dominant; above 0.6, wave making becomes dominant. For the LSD 41 Class this corresponds to a ship speed of about 12-14 knots. In the frictional regime, viscous forces dominate and resistance is proportional to velocity squared. In the residuary regime, inertial forces dominate and resistance is proportional to velocity cubed.

Ship powering requirements are determined by scale model tests and through analytic procedures. Scale model tests are conducted in both still water, and rough water to simulate heavy seas. In calculating the required installed power, predictions are made for the effect of sea state, wind, currents and other environmental effects. Once the ship has been built, it is taken to sea for a series of trials to test the performance of each installed system under actual operating conditions. One trial tests the performance of the propulsion plant. Propulsion plant Standardization Trials of *USS WHIDBEY ISLAND* (LSD 41) were conducted from 28 March to 1 April 1985 off the coast of La Jolla, California. Standardization Trials establish the relation between ship speed and propulsion plant parameters. Table 2-4 gives a summary of the important Standardization Trial parameters averaged over three runs at each speed. Frictional resistance is related to the amount of wetted surface area of the hull. Ships are operated at various conditions of loading which effect the displacement and wetted surface area of the ship. Standardization Trials were conducted at the design displacement. Design displacement is assumed throughout this thesis in determining powering requirements.

Table 2-4: Standardization Trial Results[24]

Speed (knots)	Shaft RPM	Torque (lbf-ft)	Power (hp)
11.4	81.6	232,900	3,620
14.0	100.8	332,200	6,380
1[illegible].6	121.1	477,000	11,000
19.2	140.7	638,200	17,100
19.6	142.1	673,200	19,590
20.1	150.0	721,300	20,600
21.2	15[illegible].0	811,500	24,630
21.8	165.8	885,900	27,960

The LSD 41 Class operates over two distinct speed ranges. At speeds below 10 knots the ship speed is controlled by propeller pitch. At speeds above 10 knots ship speed is controlled by shaft RPM. In the pitch controlled regime the shaft is operated at a constant 64 RPM and speed is varied by changing the pitch of the propeller. Above 10 knots propeller pitch is set at 100 percent and speed is varied by shaft RPM. The data points presented in Table 2-4 are at 100 percent propeller pitch. Within the two regimes a mostly linear relation between pitch/rpm and speed exists. Figure 7 gives the relation in the ahead direction, and Figure 8 in the astern direction.

[24]Everett I. Woo and Michael L. Klitsch, "USS WHIDBEY ISLAND (LSD 41) Standardization, Trailed and Locked Shaft Trials," David W. Taylor Naval Ship Research and Development Center, December 1985, p. 26.

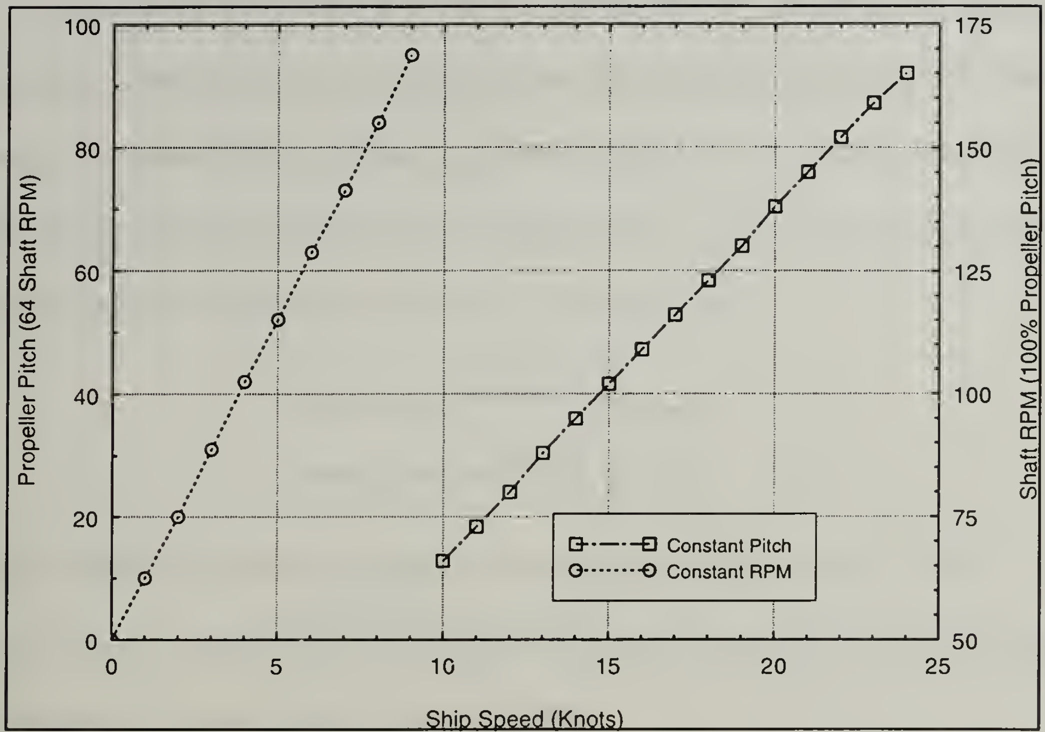


Figure 7: Ship Speed Ahead vs. RPM

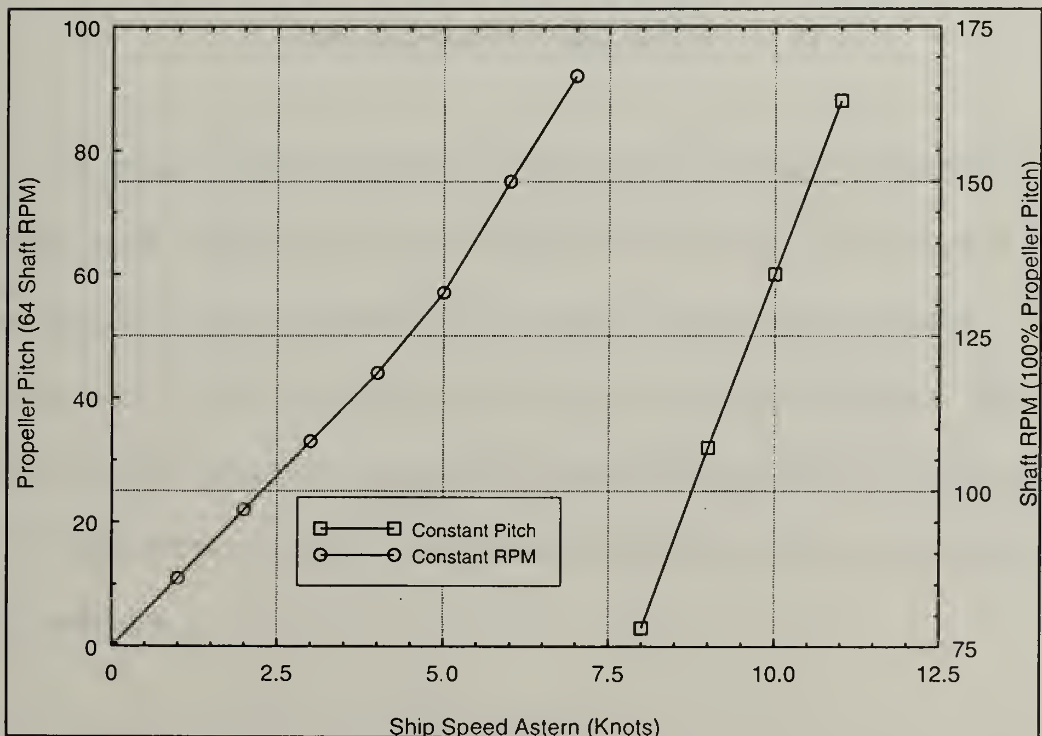


Figure 8: Ship Speed Astern vs. RPM

The two curves of Figure 7 may be represented by equations for straight lines. Ship speed is either linearly dependent on propeller pitch or shaft RPM. Equation (4) gives the ship speed equation for operation in the constant RPM region where speed is governed by propeller pitch. Equation (5) gives the ship speed equation for operation in the RPM controlled region.

$$Speed_{Ship} = 0.0948 \times Pitch_{Propeller} \tag{4}$$

$$Speed_{Ship} = 0.143 \times RPM_{Shaft} + 0.571 \tag{5}$$

Similar equations describe the astern speed dependence on pitch or RPM shown by the curves in Figure 8. Equation (6) gives the pitch controlled relation, and equation (7) gives that controlled by RPM.

$$Speed_{Ship} = 0.076 \times Pitch_{Propeller} \tag{6}$$

$$Speed_{Ship} = 0.035 \times RPM_{Shaft} + 5.23 \tag{7}$$

The greater power required to move the ship in the astern direction is reflected in the slopes of the curves of Figure 7 and Figure 8. The slope of the ahead direction curves is greater than the astern slopes due to a greater responsiveness of the ship to propulsion forces in the ahead direction. The shape of the bow presents a streamlined shape which requires less energy to move. The blunt stern section behaves as a bluff body and has a much higher drag coefficient.

The data in Table 2-5 suggests the relation between speed and power for the LSD 41 Class under the conditions given. Curve fitting the speed and shaft power data provides the speed vs. power graph given in Figure 9.

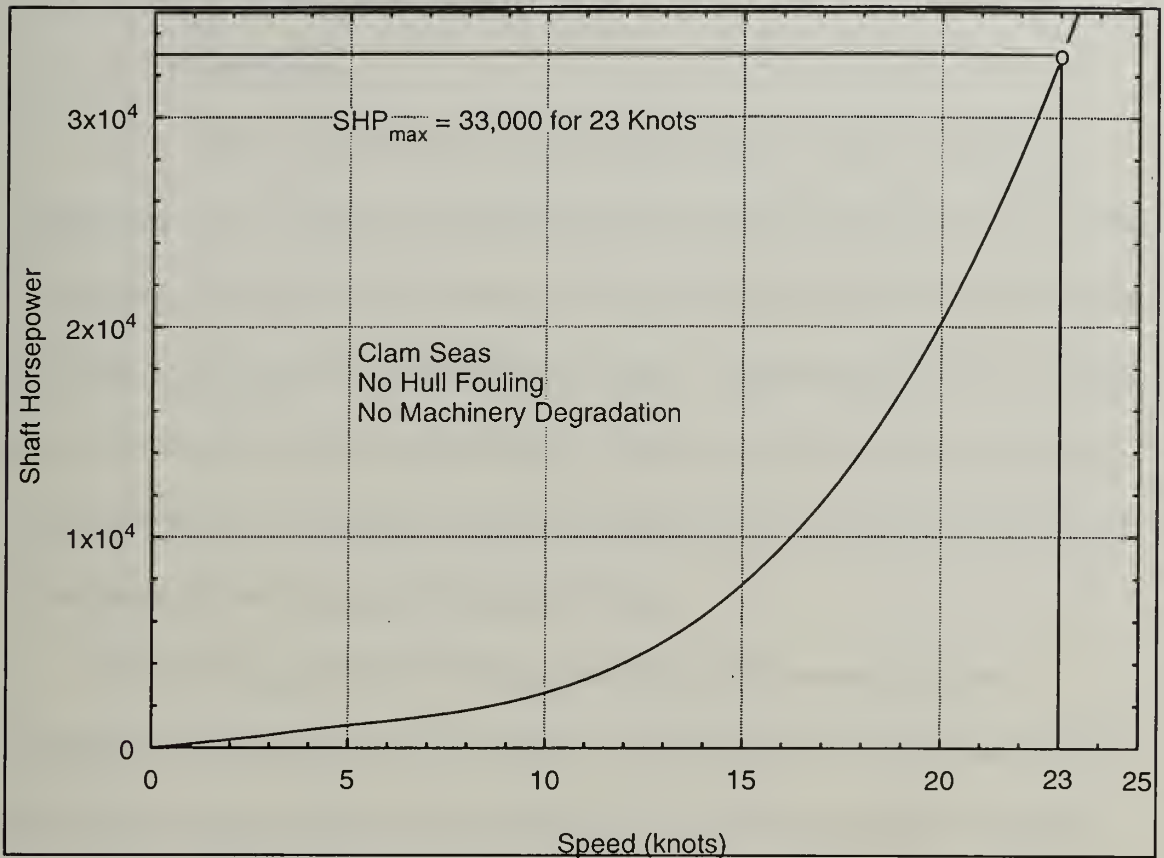


Figure 9: LSD 41 Class Speed Power Curve

The curve of Figure 9 is a combination of two curves covering the two resistance regimes. The frictional regime is represented by equation (8) and the residuary regime is given by equation (9). Equation (8) is valid up to 12 knots, and equation (9) is valid from 10 to 25 knots. The overlap of 2 knots indicates a transition from frictional to residuary resistance control.

$$Power = 9.6 \times Speed^2 + 172 \times Speed \qquad (8)$$

$$Power = 5.04 \times Speed^3 - 79.7 \times Speed^2 + 621 \times Speed - 674 \qquad (9)$$

2.3 Characteristics of Ship Operation

2.3.1 Ship Logs

U.S. Naval ships record a variety of information in official log books. These logs form a record of all significant ship events throughout its service life. This thesis reviewed two logs in detail. The information gained from log review was used to develop the class operating profile. Logs analyzed were the ships Deck Log and Engineering Smooth Log. Other logs such as engine operating log data sheets and navigation logs were examined to correlate the data found in the Deck Log and Engineering Smooth Log.

The Deck Log provides a historical record of all events deemed noteworthy throughout the life of the ship. The Deck Log records events such as: ship handling training, drills, casualties, maintenance actions, underway replenishment, underway refueling, landing craft air cushion (LCAC) operations, flight operations, major equipment trend analysis, special propulsion plant evolutions as well as information giving course, speed, distance from land and weather conditions. The time and order given for each change in engine speed and ships course are recorded in the ships Deck Log. Speed change orders are given in terms of bell order, followed by propeller pitch or shaft RPM (depending on the ship speed regime). Tables 2-5 and 2-6 show the relation between bell

Table 2-5: Ahead Bells

Bell Order	Speed (knots)	Shaft RPM	Propeller Pitch
All Stop	0	64	0
1/3	1	64	10
1/3	8	64	20
1/3	8	64	84
1/3	4	64	42
1/3	6	64	52
1/3	6	64	63
1/3	7	64	73
1/3	8	64	84
1/3	8	64	95
2/3	14	66	100
2/3	11	73	100
2/3	12	80	100
2/3	13	88	100
2/3	14	95	100
2/3	15	152	100
Standard	16	145	100
Standard	14	116	100
Standard	14	123	100
Standard	19	130	100
Full	20	138	100
Full	20	145	100
Flank	22	152	100
Flank	23	159	100
Flank	24	165	100

and shaft operation for ship speeds in the ahead and astern direction. The Deck Log is maintained as a legal record. It is the most important log kept aboard a ship. A sample Deck Log sheet is given in Appendix A.

Table 2-6: Backing Bells

Bell Order	Speed (knots)	Shaft RPM	Propeller Pitch
1/3	1	64	11
1/3	2	64	22
1/3	3	64	33
1/3	4	64	44
2/3	5	64	57
2/3	6	64	75
2/3	7	64	92
Full	8	78	100
Full	9	107	100
Full	10	135	100
Full	11	163	100

The Engineering Smooth Log records information similar to that found in the Deck Log. However, the Engineering Smooth Log only records information related to the engineering plant. Starting and stopping a major piece of equipment, clutching an engine into the reduction gear, shifting engine speed control to a remote location such as the pilot house, maintenance actions, equipment malfunction and failure, status of auxiliary systems, lube oil purification, fuel transfer and other activities are recorded in the Engineering Smooth Log. A sample Engineering Smooth Log sheet is given in Appendix A.

Engine operating logs record hourly engine speed, temperatures and pressures. These logs provide an indication of total time in operation, and abnormal, or out-of-specification conditions. Operating logs are also used to record engine parameters during trend analysis. An operating log is maintained for each operating engine. A sample log sheet is given in Appendix A.

Navigation logs record the position of the ship on an hourly basis according to position fixes. Position fixes plotted on a navigation chart indicate the track over which a ship traversed. Distances from land are readily determined from track information.

2.3.2 Operator Preference

Operator preference is the single most important factor governing the operating profile of main propulsion engines. Operator preference refers to the skill, training level, and aggressivness of those navigating the ship and responding to engine speed change orders. The skill and training level of the navigation team becomes apparent through review and comparison of the Deck Log entries for similar ship evolutions, such as, anchoring, getting underway from a pier, and mooring to a pier. More highly skilled teams will have fewer number of speed changes over the course of the evolution.

Aggressiveness is difficult to quantify, but refers to the level of dexterity demonstrated in how a ship is operated. An aggressive navigation team may not use tug boats in getting underway or mooring to a pier. The time required to perform these evolutions may also by minimized, reducing time engines are

operated at low load or at idle.

Ship port departure speed is subject to the preference of the navigation team led by the ships commanding officer. The amount of redundant equipment in operation is also largely a matter of preference. Experience shows accident boards are more forgiving of ship captains who prepared for potential problems by having equipment ready to instantly come on line should a casualty occur. This tendency for equipment redundance may be prudent for vessel operation, but results in lightly loaded equipment operating for several hours.

2.3.3 Underway Ship Operations

In developing the LSD Class Operating Profile ship operating logs were reviewed to determine time factors for engine speed/loading conditions. To remain consistent with the California Coastal Waters designation of Figure 2, ship operations out to 100 nautical miles from land were recorded in the database.

Unlike commercial ships getting underway for profit, naval vessels most often get underway for training. Commercial vessels are typically operated at speed and power combinations that maximize fuel efficiency. Commercial vessels also tend to follow tracks that minimize the distance from port to port. Although naval vessels are concerned with fuel economy, efficiency is often sacrificed for speed, maneuverability, and other operational requirements.

Underway preparations usually begin several hours before the ship actually leaves port. Shore services are disconnected and the ship becomes

self-sufficient in electric power, fresh water and steam. Normally ships electric load is carried by two lightly loaded ship service diesel engines (SSDG's) . Approximately 45 minutes prior to underway time the main propulsion diesel engines (MPE's) are started. After warming up for 10 minutes they are clutched into the reduction gear, and remain at idle for the next 35 minutes on average.

Naval ships are operated most conservatively during the transit to and from sea. As a ship maneuvers from the pier through the harbor and out to sea it is most vulnerable to collision with other vessels or to grounding. Probability of an adverse action is greatly increased by failure within the propulsion or electrical plant. To decrease failure probability, redundant systems and equipment are in operation during the time that a ship transits to or from sea. A special operating condition, Sea and Anchor Detail, governed by the Restricted Maneuvering Doctrine (RMD) is manned to maximize equipment and personnel readiness. A normal Sea and Anchor Detail typically lasts for about two hours as a ship transits in and out of port.

The traditional underway usually begins with the shafts turning in opposite directions to twist the stern of the ship away from the pier. Next the shaft directions are reversed and the bow of the ship moves away from the pier. This series of engine orders may number ten bell changes over a span of five minutes. During this phase of maneuvering the engines are essentially steady-state only briefly, or mostly transient, before the next bell. Away from the pier, the ship slowly makes headway using a 1/3 bell for three to five knots. Clear of

close obstacles, ship speed is often increased to ten knots for the remainder of the transit to open water. When in open water, ship speed then becomes more discretionary for the navigation team.

Once at sea, the ship secures from the Sea and Anchor Detail and the RMD. After securing from RMD most ships typically shift engineering plant operation to maximize fuel efficiency and minimize machinery wear. The normal post RMD lineup consists of one MPE per shaft and two SSDG's in parallel. The maximum speed that can be attained by LSD 41 Class in this lineup is roughly 18 knots. Evolutions requiring more speed and power necessitate additional MPE's on the line.

U.S. Navy ships operate off the Southern California Coast in the SOCAL Operation Area, and off the Norfolk, Virginia area in the VACAPES Operation Area. These operating areas are within 100 nautical miles of land and are approximated in Figures 10 and 11. While operating in these areas ships will conduct: man overboard drills, shiphandling training, shipwide warfighting and casualty control drills, underway replenishment to resupply with fuel, ammunition and stores, flight operations, and trend analysis on MPE's and SSDG's.

Figure 10: Southern California (SOCAL) Operating Area (Approximate)

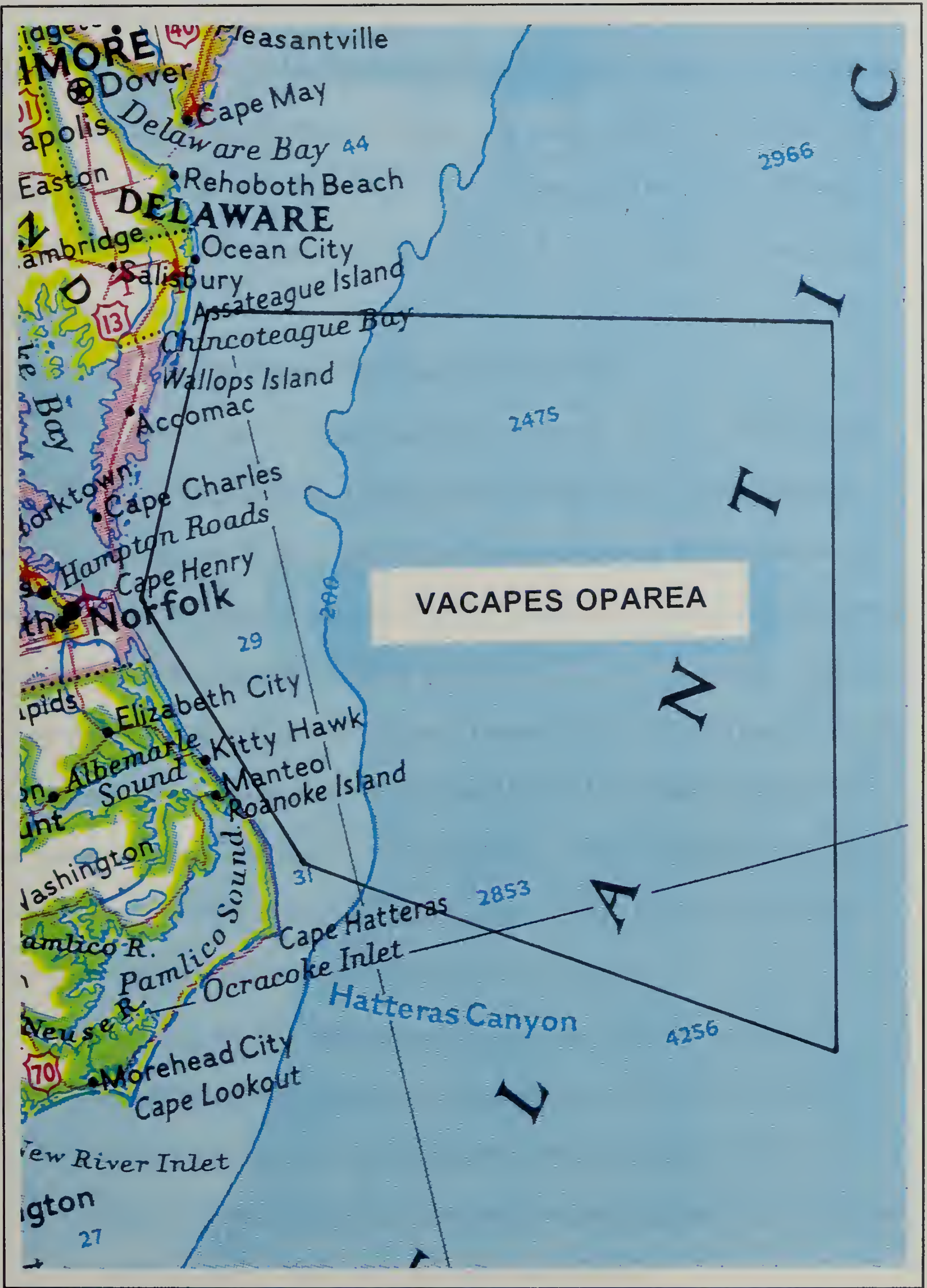


Figure 11: Virginia Capes (VACAPES) Operating Area (Approximate)

The LSD 41 Class frequently conducts amphibious assault exercises with embarked Landing Craft Air Cushion (LCAC) craft both at sea and off the coasts of southern California and North Carolina. For these operations the ship may be steaming at between 10 and 13 knots, or it may be at anchor. Each of these evolutions exercises the propulsion plant through a wide range of speed and power combinations.

2.4 LSD 41 Class MPE and SSDG Operating Profile

The wide range of operator preferences coupled with the variety of ship evolutions complicates the development of a standard naval ship operating profile. The application of commercial or civilian standards to describe naval ship operation is inappropriate. Four LSD 41 Class ships logs, covering several months of operation within 100 nautical miles of land, were analyzed. Logs of ships from the east and west coasts were reviewed to distinguish geographically related differences. Two ships were homeported in Little Creek, Virginia, and two were homeported in San Diego, California. Table 2-7 presents a summary of the operational time evaluated. Appendix B provides data summaries for: each ship, breakdown by coast, and the composite profile.

Developing the ship operating profile involved determining time of operation at specific speed and power combinations. Figure 12 provides a flowchart of the logic used in the Lotus 123W database used to perform the profile analysis. Table 2-8 gives the four ship composite operating profile of the LSD 41 Class operating within 100 nautical miles of land.

Table 2-7: LSD 41 Class Ship Data Summary (All Times in Minutes)

	LSD 43	LSD 44	LSD 46	LSD 47
Name	Fort McHenry	Gunston Hall	Tortuga	Rushmore
Coast	West	East	East	West
Time Period (1993)	12 July 16 December	14 September 30 November	3 March 20 September	1 June 16 December
Main Propulsion Engine Data				
Data Points	5,011	2,816	4,267	3,013
Time Covered	252,324	133,052	159,845	145,517
Time Secured	74,589	54,499	76,872	51,025
Time Running	177,735	78,553	82,973	94,492
Time Warmup	1,458	1,306	1,892	1,571
Time @ Idle	2,886	1,725	2,357	1,155
Time @ Power	173,391	75,522	78,724	91,766
Ship Service Diesel Engine Data				
Data Points	992	414	862	809
Time Covered	239,750	146,895	210,854	182,942
Time Secured	66,127	38,516	90,442	55,328
Time Running	173,623	108,379	120,432	127,614
Time Warmup	1,602	1,664	2,101	3,065
Time @ Idle	1,039	4515	2,329	1,275
Time @ Power	170,982	106,300	116,002	123,274

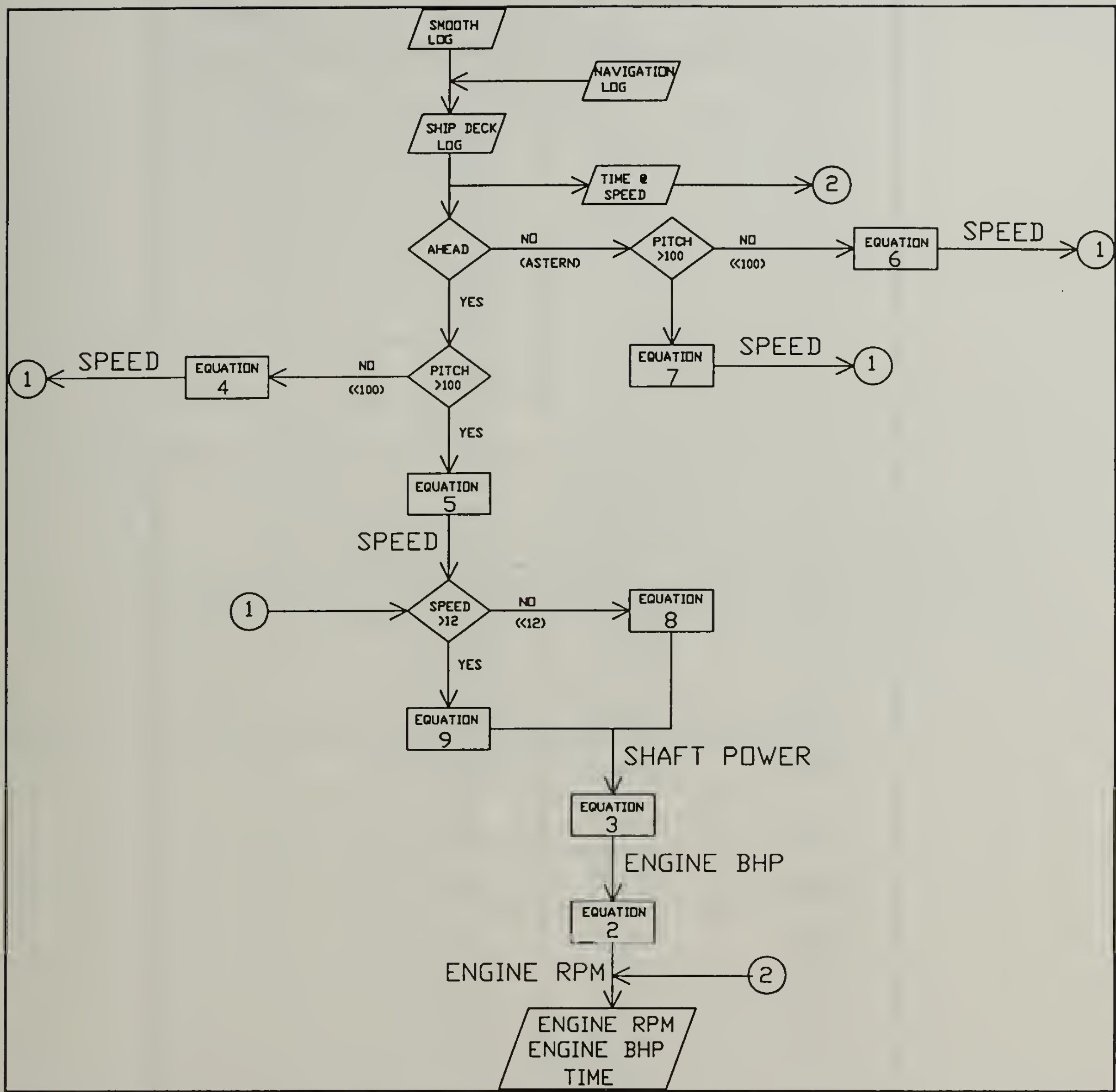


Figure 12: Operating Profile Flow Chart

Table 2-8: LSD 41 Class Composite Operating Profile Time Factors

Ship Speed (knots)	Engines/Shaft		Total
	1	2	
Idle	0.081		0.081
1	0.008	0.001	0.002
2	0.001	0.015	0.011
3	0.001	0.008	0.008
4	0.008	0.003	0.007
5	0.102	0.033	0.139
6	0.005	0.003	0.008
7	0.017	0.005	0.022
8	0.014	0.0[illegible]4	0.015
9	0.008	0.003	0.008
10	0.083	0.056	0.139
11	0.0[illegible]5	0.008	0.017
12	0.028	0.012	0.040
13	0.025	0.015	0.035
14	0.028	0.0[illegible]0	0.0[illegible]8
15	0.057	0.034	0.088
16	0.041	0.015	0.056
17	0.105	0.015	0.120
18	0.015	0.011	0.026
19	0.000	0.017	0.017
20	0.000	0.034	0.034
21	0.000	0.015	0.015
22	0.000	0.027	0.027
23	0.000	0.019	0.019
24	0.000	0.035	0.035

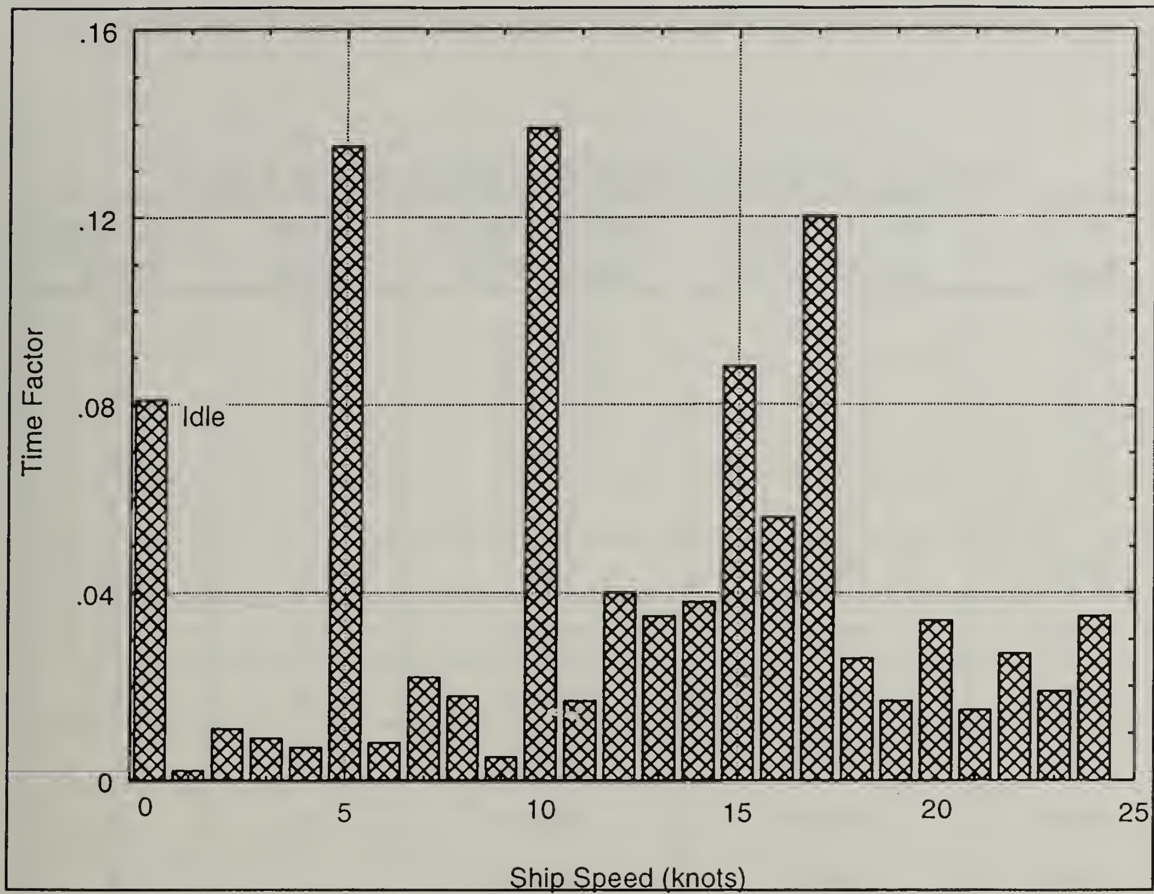


Figure 13: LSD 41 Class Composite Speed Operating Profile

The ship speeds and composite time factors given in Figure 13 should be representative of most naval diesel powered ships while they operate in areas close to shore. The speed profile given in Figure 13 shows that the LSD 41 Class operates primarily in the higher speed ranges centered around 17 knots. Time factor spikes exist at 0, 5 and 10 knots. The value for 0 knots is comprised of cold and warm idle. Cold idle has a time factor of 0.014 and warm idle 0.067, making warm idle greater than cold idle by a factor of five.

The method illustrated by the flowchart of Figure 12 links ship speed to MPE speed and power. Table 2-9 gives this relation for ship speeds below 10

knots and Table 2-10 shows this relation for speeds 10 knots and above.

Table 2-9: Composite MPE Operation Points (0-9 knots)

Engines/ Shaft	Ship Speed	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
0	0	Cold Idle	0.000	0.014
0	0	Warm Idle	0.026	0.064
2	2	0.387	0.026	0.012
1	2	0.387	0.018	0.001
2	3	0.387	0.018	0.005
2	4	0.387	0.026	0.033
2	5	0.387	0.038	0.033
1	3	0.387	0.037	0.001
2	6	0.387	0.038	0.003
2	7	0.387	0.045	0.005
1	4	0.387	0.052	0.002
2	8	0.387	0.054	0.004
[illegible]	9	0.387	0.065	0.003
1	5	0.387	0.065	0.002
1	6	0.387	0.077	0.005
1	7	0.387	0.091	0.017
1	8	0.387	0.108	0.014
1	9	0.387	0.129	0.002

Table 2-10: Composite MPE Operation Points (10-24 knots)

Engines/ Shaft	Ship Speed	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
2	10	0.398	0.079	0.056
1	10	0.398	0.[illegible]98	0.083
2	11	0.440	0.098	0.002
2	12	0.48[illegible]	0.122	0.012
2	13	0.531	0.152	0.010
2	17	0.573	0.189	0.010
1	11	0.440	0.195	0.015
2	1[illegible]	0.615	0.234	0.031
1	12	0.48[illegible]	0.243	0.028
2	16	0.658	0.288	0.015
1	13	0.531	0.303	0.028
2	17	0.440	0.352	0.015
1	14	0.573	0.378	0.028
2	18	0.742	0.426	0.041
1	1[illegible]	0.615	0.098	0.057
2	19	0.735	0.513	0.017
1	16	0.658	0.576	0.041
2	20	0.833	0.612	0.034
1	17	0.712	0.724	0.105
2	21	0.875	0.724	0.015
2	2[illegible]	0.917	0.851	0.028
1	18	0.735	0.853	0.015
2	23	0.958	0.993	0.019

2	24	1.000	1.000	0.035

The SSDG operating profile was much simpler to determine than the ship speed profile. In this case, the Engineering Smooth Log and engine operating logs were reviewed. Table 2-11 provides the SSDG composite operating profile summary.

Table 2-11: Composite SSDG Engine Operating Profile Time Factors

Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
1.000	0.000	0.026
1.000	0.192	0.007
1.000	0.400	0.200
1.000	0.500	0.464
1.000	0.600	0.266
1.000	0.808	0.026
1.000	1.000	0.011

Figure 14 describes the SSDG operating profile graphically. This graph clearly indicates that operation of the LSD 41 Class SSDG's is concentrated around the 50 percent load point.

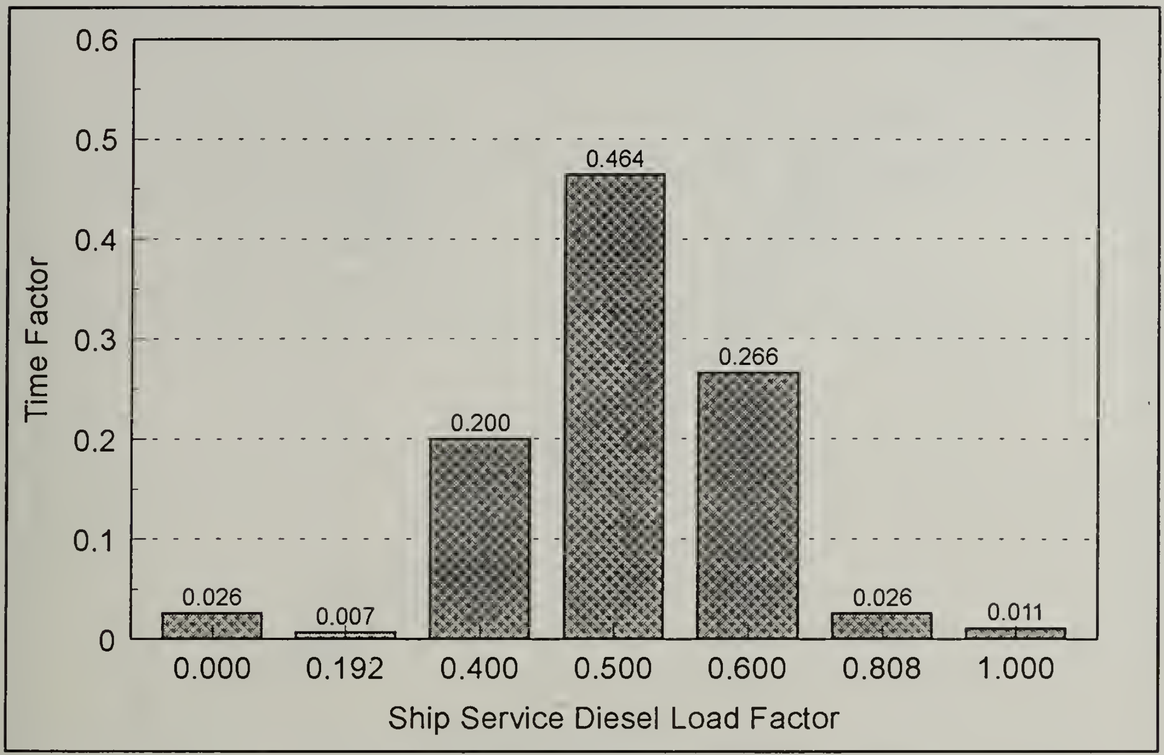


Figure 14: LSD 41 Class Composite SSDG Operating Profile

2.5 Operating Profile Coastal Variation

The ship operating profile provided in Figure 13 is a composite of four ships profiles. Figure 15 illustrates the variation between the four ships. Figure 16 delineates the variation between ships operating on the east and west coasts and compares them to the composite operating profile.

The comparison between ships in Figure 15 shows that each ship is operated in generally the same manner. Trends given by the four curves are of the same shape; they track within a band of 18 percent variation. The greatest variation occurs at speeds above 10 knots. The indicated variation is largely dependent upon the evolutions each ship was engaged in as well as the

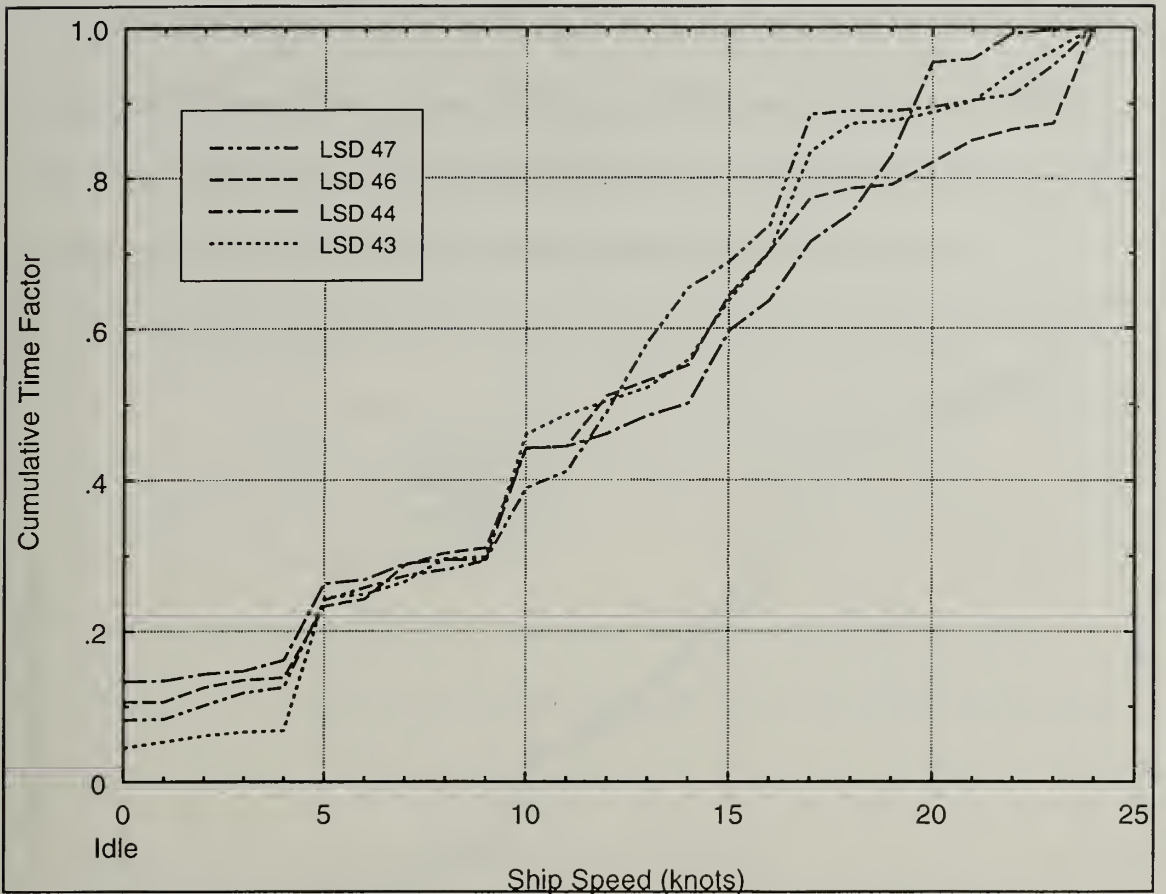


Figure 15: Ship Operating Profile Cumulative Time Factor Comparison

preference of the individual operator.

The comparison shown in Figure 16 is much closer than the comparison of Figure 15. In Figure 16, the widest variation occurred at 17 knots with a span of 15 percent. Except for the region between 16 and 19 knots the three curves tracked very close to one another. The variation below 4 knots was due to differences in time spent at idle. West coast ships spent approximately 7 percent more time at idle than did east coast ships. The greater amount of time spent by west coast ships at idle is primarily due to the layout of the harbor and geometry of the piers. The profile followed by west coast ships takes more time

than east coast ships to reach open water. The use of tugs by west coast ships is also greater due to the greater difficulty in maneuvering close to the nested piers. The composite curve tracked closest to the east coast indicating that the operating profile was most heavily influenced by east coast ships.

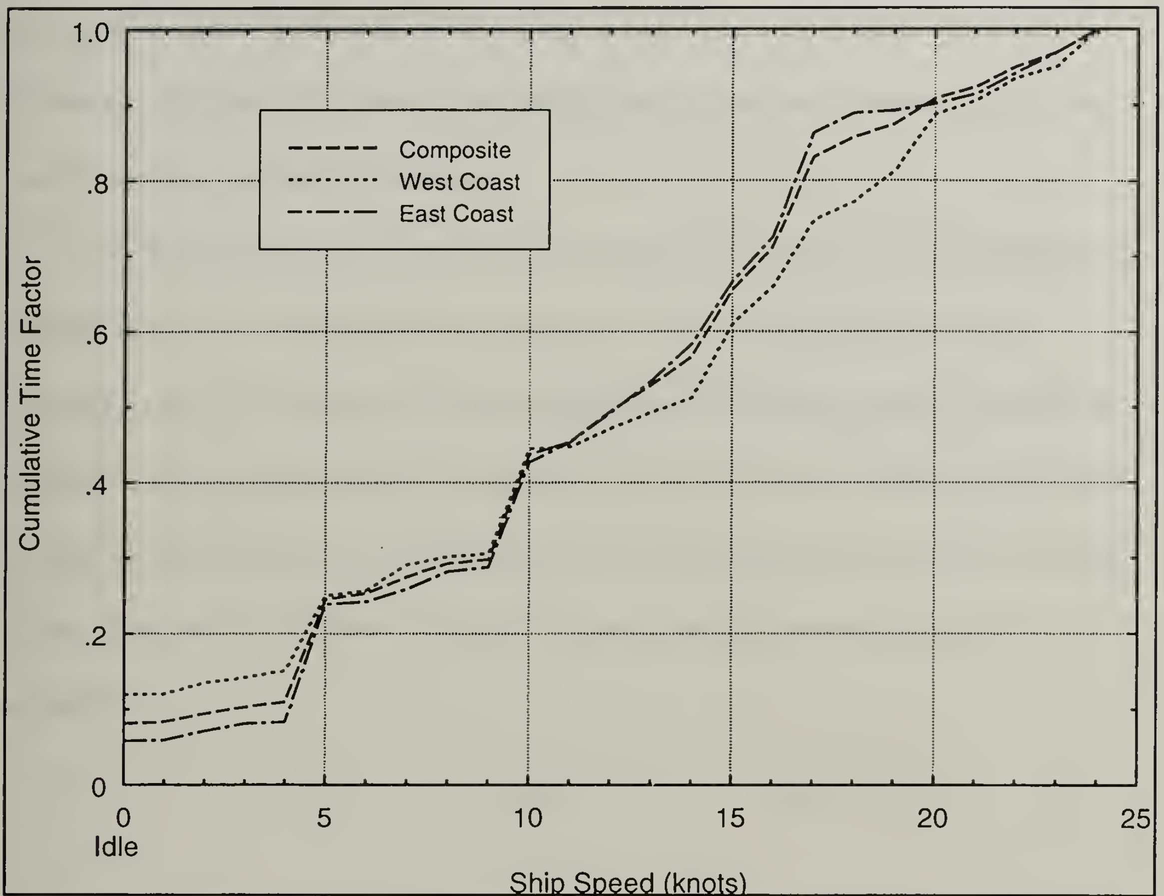


Figure 16: Operating Profile Cumulative Time Factor Comparison by Coast

Chapter 3: NAVAL DIESEL ENGINE DUTY CYCLE DEVELOPMENT

3.1 Naval Main Propulsion Diesel Engine Duty Cycle

A duty cycle must provide an accurate model of the range of speed and power points at which an engine is operated, and also be concise and easy to use. A duty cycle consisting of five to ten modes is preferable to one using ten to fifteen, provided it accurately reflects engine operation. However, accuracy should not be sacrificed for brevity.

To date, most duty cycles have been developed for generic application to a wide variety of land based power systems. These systems are on-road vehicles, non-road vehicles and heavy equipment, railroads, power generating facilities and portable industrial equipment. For land based propulsion systems a direct relation between output required and vehicle weight and friction usually exists. The relation to overcome static friction (initiate motion) is given in equation 10.

$$F=\mu L \qquad (10)$$

Where the friction force, F, is proportional to the normal force, L, and μ is the coefficient of static friction. Once the vehicle begins to move, its motion is governed by the dynamic relation given as equation 11.

$$F_R=\frac{\nu_s}{\nu_r}F_K \qquad (11)$$

Where total rolling friction, F_R, is proportional to the ratio of slip velocity, ν_s, to

rolling velocity, ν_r, and F_K the kinetic coefficient of sliding friction. The ratio of slip velocity to rolling velocity describes slippage to rolling amount occurring at the interface between two bodies in relative motion. Equations 10 and 11 apply to each component in the drive train from piston rings/cylinder walls to tires and road surface. Since equations 10 and 11 describe linear motion, the rule of superposition may be used to sum their cumulative effect. Equation 3 defines mechanical efficiency and is closely related to the additive effects of equation 10 and 11. Air resistance contributes a greater proportion of the total resistance to land vehicle motion. This is due to smaller overall vehicle weights.

To achieve a given speed, larger vehicles will have larger propulsion engines. For power generation systems, power output is related to generator size. Size dictates torque and power requirements of the prime mover. For a given application, the prudent designer selects an engine size optimized for both fuel efficiency and power output. For example, locomotive engines are designed to pull a specific number and weight of railroad cars at an optimum rail speed. Regardless of the manufacturer or size of the land vehicle, the percent plant output for a given speed is fairly constant. Automobiles and trucks require similar relative engine power output to travel at normal highway speeds. Semi-tractor-trailer on-road trucks use an equivalent speed/power relation throughout design speed ranges. The wide variety of land based equipment and engine combinations is readily modeled by generic duty cycles. For example, in most applications the thirteen duty cycles of ISO 8178-4 effectively cover the

spectrum of land based reciprocating internal combustion engine operation.

Section 2.2 describes the forces resisting ships motion. Underwater hull form shape and wetted surface area determine the powering requirement for a given speed. The simple relations of equations 10 and 11 do not describe ship resistance; therefore, the hull specific speed power relation, typified by Figure 9, must be used. Commercial ship engines are designed to provide optimum fuel economy at some cruising speed. Engines are sized according to ships full load weight. For an established cruising speed, the fraction of rated engine RPM and engine power are relatively constant. The theory behind ISO 8178-4 duty cycles E1, E2 and E3 reflects operation at a few engine speed/power combinations. For most of their operational life these ships cruise at between 15 and 20 knots.

Naval ship engines are sized for performance rather than efficiency. The ship hull is established and propulsion plant sized to provide some design sustained speed in excess of the endurance (cruise) speed. For example, the operating profile of Figure 13 shows that the LSD Class has a top speed of 24 knots. However, it operates most frequently at 17 knots. This apparent overcapacity in propulsion plant power results in an extremely wide range of engine operating combinations. The majority of naval ship hulls are displacement type but of many different shapes. Each has a distinct speed power relation. The diversity of diesel engine sizes and types, coupled with the wide variety of hull form designs, complicates the use of generic speed power simplifications.

A study comparing engine horsepower to vehicle weight shows that consistency exists in the form of the relation between vessels of different employment and land vehicles of different sizes. Figure 17 depicts several curves of horsepower (HP) normalized to vehicle weight or vessel displacement (Δ) plotted against weight/displacement. The curves have the same general shape, given by the relation of equation 12.

$$\frac{HP}{\Delta} = \alpha \times \Delta^{-\beta} \qquad (12)$$

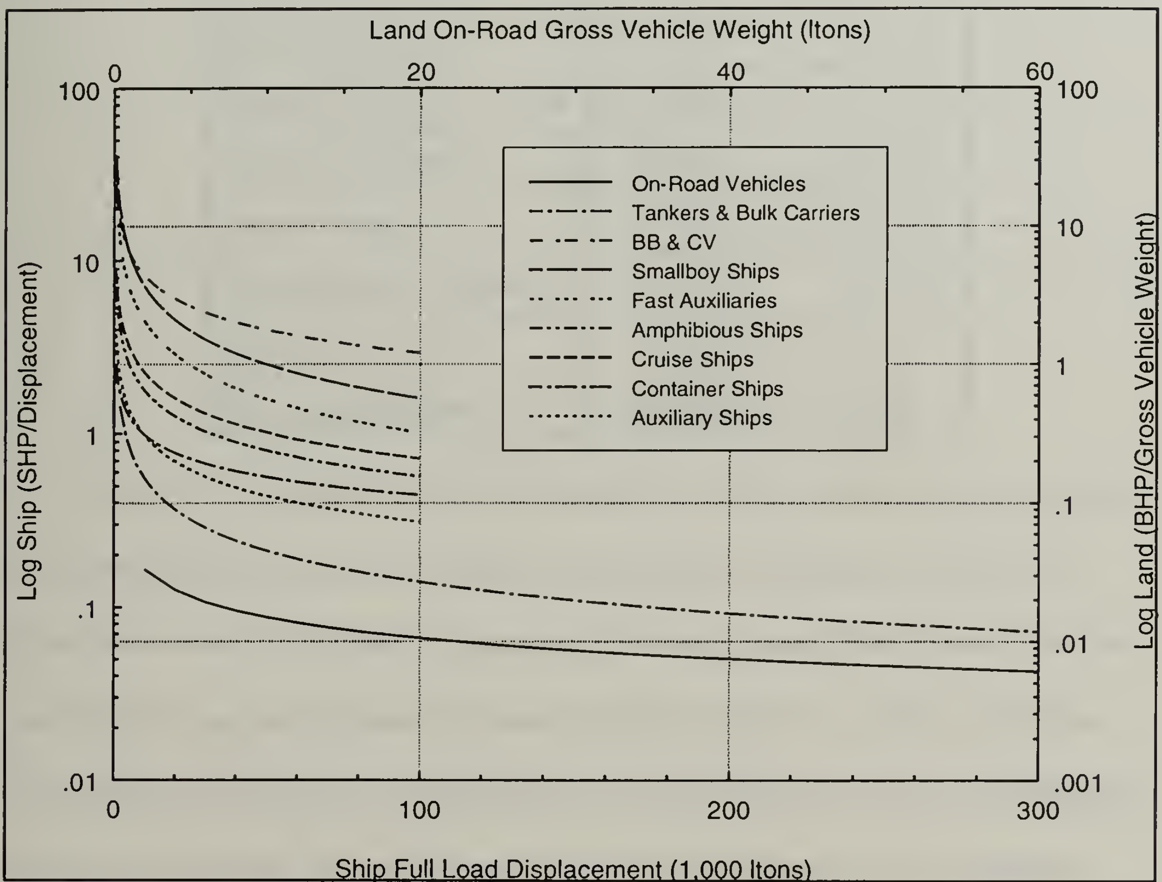


Figure 17: Power Normalized to Weight versus Weight

Rearrangement of equation 12 gives the relation between horsepower

and vehicle weight given by equation 13.

$$HP=\alpha\times\Delta^{(1-\beta)} \qquad (13)$$

The curve fit constants α and β describe vessel/vehicle shape and resistance parameters. Table 3-1 gives the values α and β for the curves of Figure 17.

Table 3-1: Horsepower to Displacement Coefficients

Figure 17 Curve	α	β
BB & CV	23.2	0.45
Smallboy Ships	31.9	0.60
Fast Auxiliaries	20.1	0.65
Auxiliary Ships	3.095	0.50
Amphibious Ships	5.647	0.50
Cruise Ships	7.164	0.50
Tankers/Bulk Carriers	2.77	0.60
Container Ships	2.21	0.35
On-Road Vehicles	0.0473	0.50

BB & CV type ships are battleships and aircraft carriers, smallboy ships are warships cruiser size and smaller, fast auxiliary ships have a maximum speed in excess of 25 knots. By grouping the ships evaluated by ship type the perturbation caused by speed differences were avoided. α tends to describe ship speed as a function of displacement. Large fast ships, such as battleships and aircraft carriers, have a higher α than large slow ships such as tankers. This trend is continued into the on-road regime with α on-road several orders of magnitude less than marine vessels. β is related to the shape of the individual

curve, expressing the range, or scatter, of ships evaluated within a ship classification. The higher value of β indicates closer correlation between individuals within a category. The limit of β is likely much less than unity.

Figure 17 shows the wide variability in displacement and ship power requirements. Some correlation does exist between on-road land based and marine vehicles. However, four orders of magnitude separate the nine vehicle types studied. The simplistic analysis represented by equations 12 and 13 are inadequate to accurately predict engine power requirements for each application. Each hull design has a unique resistance relationship resulting in a myriad of diesel engine options. For these reasons, a simple four or five mode duty cycle is not appropriate to describe naval ship engine operation. Rather, the operating (speed) profile must be determined then engine speed and power calculated based on appropriate relationships. The process is essentially the same given in Figure 12. Figure 18 provides a flow chart for determining the individual ship type propulsion plant duty cycle.

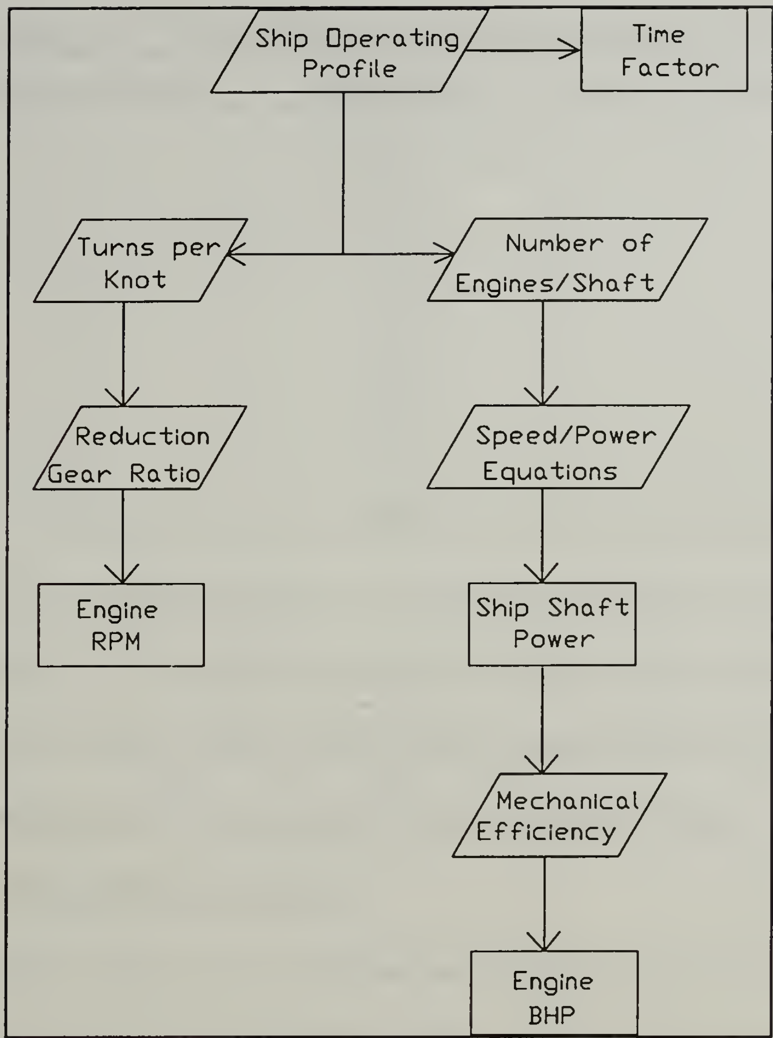


Figure 18: Naval Ship Duty Cycle Determination

The entering arguments of Figure 18 are the standard composite operating profile and ship specific propulsion train and powering information. The composite operating profile of Figure 13 has been reduced from 25 to seven speed points. Speed points and associated time factors are given in Table 3-2. Ranges covered by each speed point were grouped by engine speed and power around each major speed spike indicated in Figure 13.

Table 3-2: Consolidated Naval Ship Operating Profile

Ship Speed (knots)	Time Factor	Speed Range (knots)
0	0.083	Idle - 1
5	0.160	2 - 7
10	0.208	8 - 12
15	0.160	13 - 15
1[illegible]	0.200	16 - 18
20	0.093	19 - 22
24	0.054	23 - 24

By using the method of Figure 18 a naval ship specific duty cycle may be readily developed. As some ships may have multiple engines clutched to each shaft, care must be taken to ensure each engine speed/power combination is adequately represented for all machinery lineups normally used.

3.2 LSD 41 Class MPE Duty Cycle

The LSD 41 Class may be operated with either one or two engines per shaft. Both conditions must be included in the resulting duty cycle. The LSD 41 MPE Duty Cycle, as developed from the method given in Figure 18, is given in Table 3-3.

Table 3-3: LSD 41 Class MPE Duty Cycle

Mode	Ship Speed	Engines/ Shaft	Engine Speed (% of Rated)	Engine Power (% of Rated)	Time Factor
1	0	0	Idle	0.000	0.083
2	5	1	0.387	0.068	0.064
3	5	2	0.387	0.032	0.128
4	10	1	0.398	0.158	0.077
5	10	2	0.398	0.078	0.141
6	15	1	0.615	0.468	0.051
7	15	2	0.615	0.234	0.109
8	17	1	0.700	0.700	0.040
9	17	2	0.700	0.352	0.160
10	20	2	0.833	0.612	0.093
11	24	2	1.000	1.000	0.054

3.3 T-AO 187 Class MPE Duty Cycle

To demonstrate the use of Figure 18 in developing duty cycles for other naval ships, the T-AO 187 Class was selected. The T-AO 187 Class of fleet oilers is equipped with two shafts. Each shaft is driven by a single Colt-Pielstick PC4-2 diesel engine. The combined 32,540 bhp propels the two shafts and powers the 39,400 ton ship to a maximum speed of just over 19 knots. Resistance and powering information was determined by using the *MONO-LA* variant of the computer program *Advanced Surface Ship Evaluation Tool (ASSET)*. The ship is RPM limited since it reaches rated RPM before reaching rated power. Curve fitting the speed/power data produced the required frictional and residuary resistance speed power relationships. Table 3-4, and equations

14 and 15 give the data required to enter Figure 18 to compute T-AO 187 Class MPE Duty Cycle.

Table 3-4: T-AO 187 Propulsion Plant Data

Engine RPM	
Turns per knot	4.86
Reduction Gear Ratio	4.24
Engine BHP	
Mechanical Efficiency	0.975

Frictional resistance regime is governed by equation 14 and is valid from 0 to 12 knots.

$$SHP = 65 \times S^2 - 267 \times S + 155 \qquad (14)$$

Residuary resistance regime is represented by equation 15 and is valid from 12 to 20 knots.

$$SHP = 22 \times S^3 - 756 \times S^2 + 10300 \times S - 47000 \qquad (15)$$

S in equations 14 and 15 is ship speed in knots.

Table 3-5 illustrates the T-AO 187 Class MPE Duty Cycle using the method of Figure 18 and the operating profile developed in Chapter 2. The T-AO 187 Class operating profile has been approximated by the LSD 41 Class profile for illustrative purposes. Use of the LSD 41 Class profile may not be a reasonable assumption, a seperate profile should be developed.

Table 3-5: T-AO 187 Class MPE Duty Cycle

Mode	Ship Speed	Engine Speed (% of Rated)	Engine Power (% of Rated)	Time Factor
1	0	Idle	0.000	0.083
2	5	0.500	0.014	0.192
3	10	0.5[illegible]	0.0126	0.218
4	15	0.774	0.367	0.160
5	17	0.876	0.558	0.293
6	19	1.000	0.917	0.054

3.4 LSD 41 Class SSDG Duty Cycle

Typical electric plant loads for LSD 41 Class ships vary from 1,500 to 1,800 kW delivered at between 1,100 and 1,500 amps. Since rated generator size is 1,300 kW, SSDG's of the LSD 41 Class are most often operated at approximately 50 percent load. Data given in Table 2-11 suggests a reasonable six-mode, constant speed duty cycle. Table 3-6 provides the LSD 41 Class SSDG Duty Cycle.

Table 3-6: LSD 41 Class Ship Service Diesel Engine Duty Cycle

Mode	Engine Speed	Engine Load	Time Factor
1	1.000	0.000	0.033
2	1.000	0.400	0.200
3	1.000	0.500	0.464
4	1.000	0.600	0.266
5	1.000	0.800	0.026
6	1.000	1.000	0.011

Variability of engine/generator set combinations and ship electrical power requirements impedes development of a SSDG operating profile appropriate for all ship types. Most naval SSDG's are operated at much higher loads than typically found on the LSD 41 Class. ISO 8178-4 constant speed duty cycles D1 or D2, illustrated in Table 1-13, may be appropriate for naval application. Atypical operation of LSD 41 Class SSDG's requires the more detailed duty cycle delineated in Table 3-5. Realistically, SSDG data is available onboard each U.S. Naval ship to easily calculate time factors for adjusting the duty cycle of Table 3-5, ISO 8178-4 D1 or D2.

Chapter 4: Duty Cycle Comparison

Diesel engine duty cycle comparisons were performed to validate methodology used in preparing naval ship duty cycles, and compare them to industry accepted standards.

4.1 Comparison Methodology

The MPE comparisons were performed using emission contour maps provided in *The Motor Ship* article "Designers Anticipate Engine Emission Controls", of August 1992. Emission contour maps plot emissions as a function of engine speed and power. Three dimensional information is displayed as a contour map in two dimensions. Contour maps provided in *The Motor Ship* were based on the Colt-Pielstick PC4-2B engine with specific emission levels given in g/kW-hr. Graphs were normalized to rated power and RPM to give maximum speed and power values of unity. Emission curves were converted from metric to english units of g/bhp-hr. Curves were then reproduced in the computer program *Easy Plot* to facilitate comparison. Figures 19 to 22 illustrate the emission contour maps used. Engine power was normalized to Power Fraction using Equation 16 and engine RPM was reduced to RPM Factor by Equation 17.

$$Power_{Fraction}=\frac{Power_{Point}}{Power_{Rated}} \tag{16}$$

$$RPM_{Factor}=\frac{RPM_{Point}-RPM_{Idle}}{RPM_{Rated}-RPM_{Idle}} \tag{17}$$

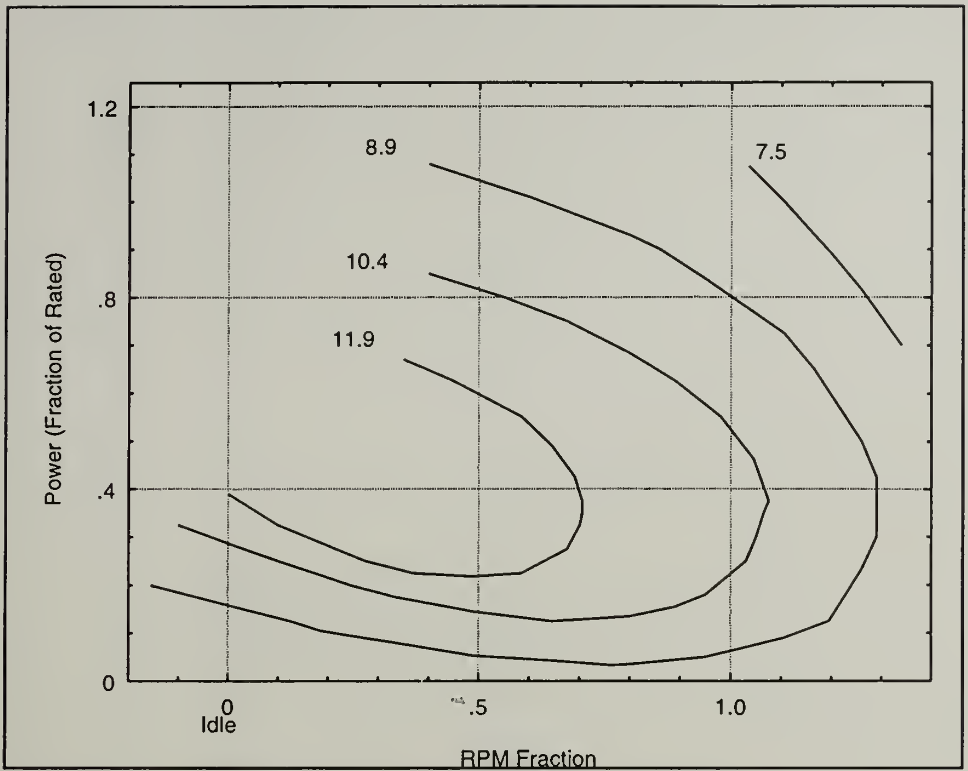


Figure 19: NO_x Emission Contour Map (g/bhp-hr)

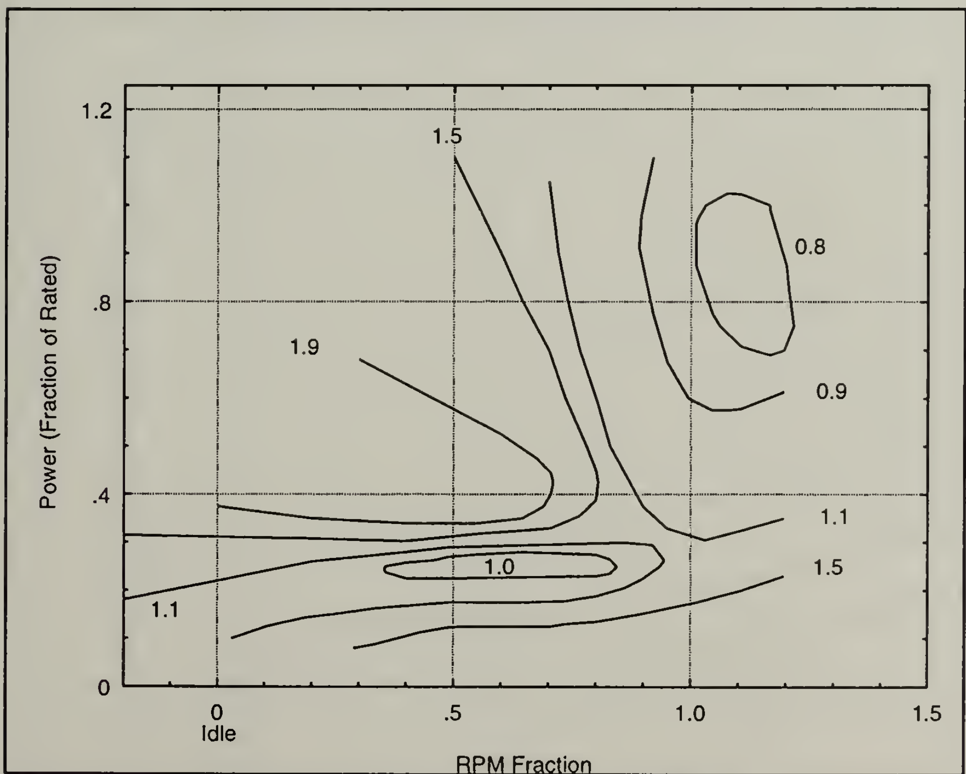


Figure 20: CO Emission Contour Map (g/bhp-hr)

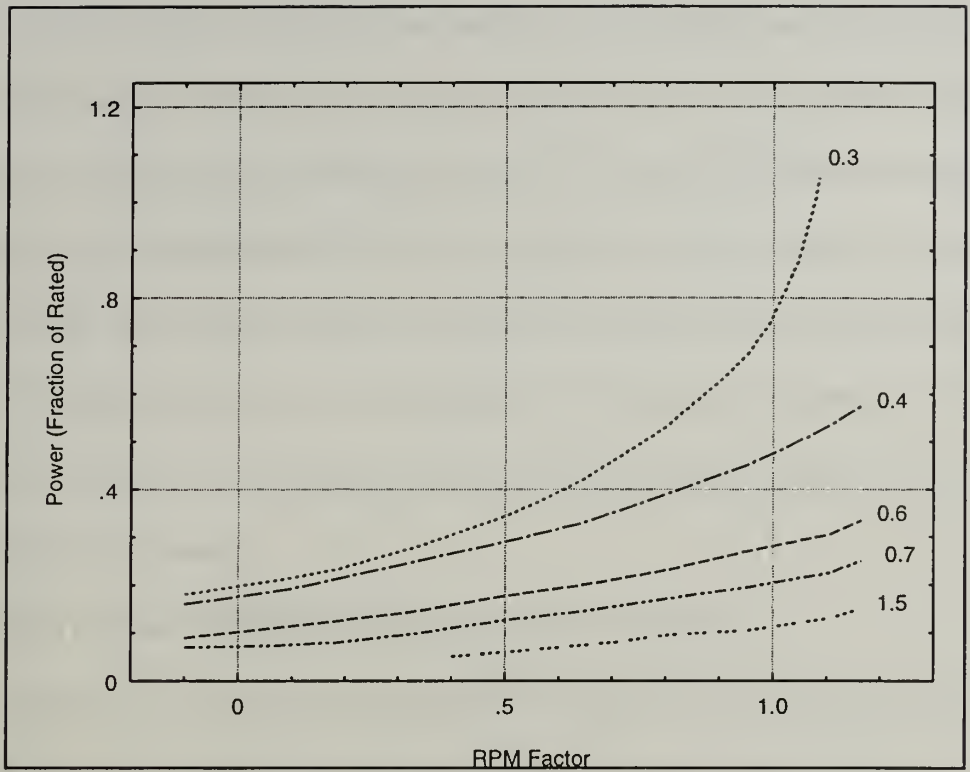


Figure 21: HC Emission Contour Map (g/bhp-hr)

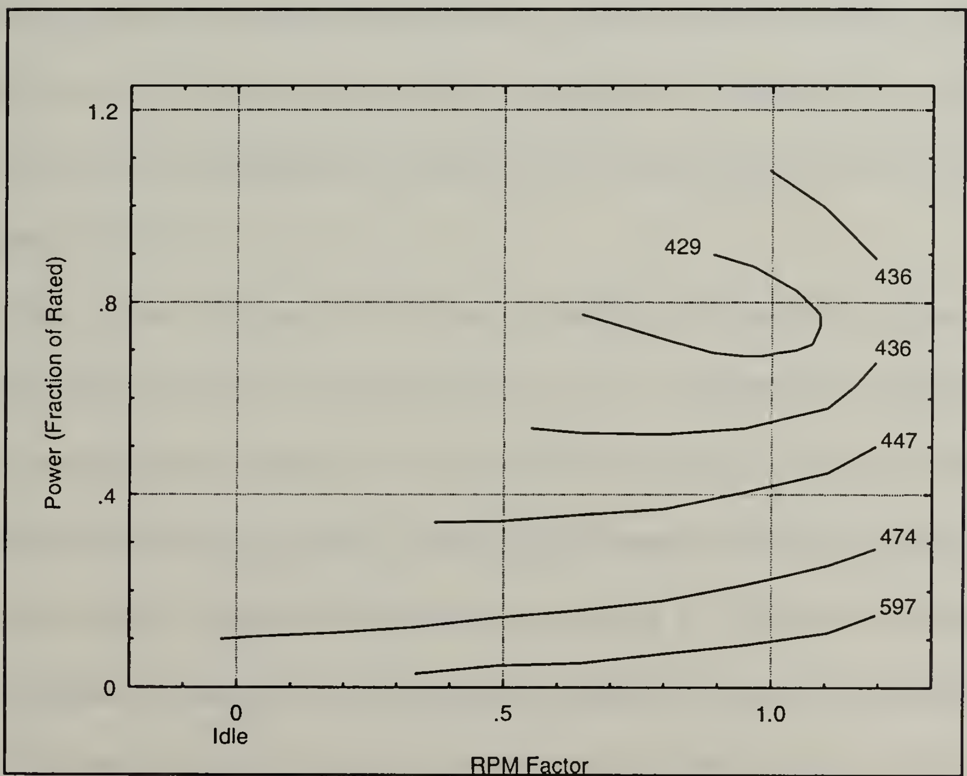


Figure 22: CO_2 Emission Contour Map (g/bhp-hr)

Engine emission analysis was performed by plotting each duty cycle on the four emission contour maps. Emission values for the idle condition were based on the work of V. W. Wong in his work "Transient Emissions Breakdown Analysis", *Cummins Report 0749-79007* of 23 May 1979. Average idle emission for nine engines was calculated as a percent of emission level observed at power. For NO_X this value was 2.6 percent of the maximum observed, or 0.31 g/bhp-hr in Figure 19. Appendix C contains the data used to generate the emission contour maps.

4.2 LSD 41 Class MPE Duty Cycle Emission Prediction

Propeller curve plots of single and twin engines per shaft, from the data of Table 2-9 and 2-10, were superimposed on the emission contour maps. Figures 23 to 26 provide these superimposed graphs. Brake specific emission levels were then read from the curves by linear interpolation. Values given describe engine emissions as a function of ship speed. Plots of these curves are shown in Figures 27 to 30.

The curves of Figure 27 to 30 are consistent with data found in the literature. NO_X production, illustrated in Figure 27, is maximized at highest cylinder temperatures. Maximum NO_X production occurs at maximum brake mean effective pressure (bmep), which is approximately 85 percent rated power and engine speed. Maximum bmep occurs very near 17 knots for the engine data illustrated in these curves. Table 2-8 shows that 17 knots is the second highest frequency of occurrence in the composite operating profile. This is not

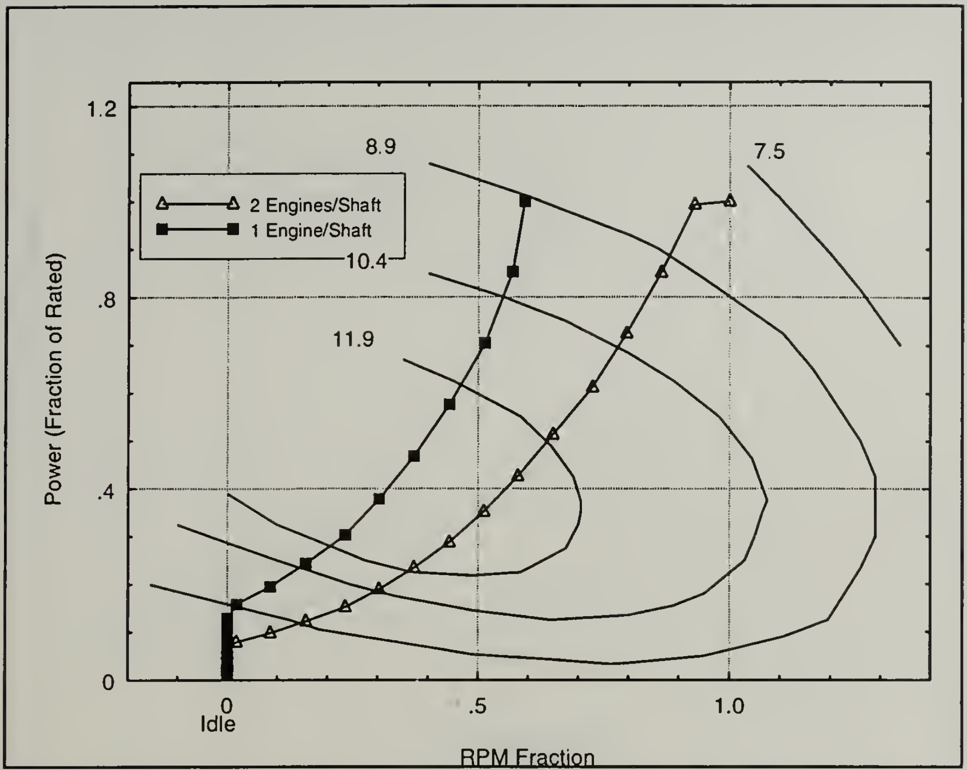


Figure 23: LSD 41 MPE NO_X Emission Contour Map (g/bhp-hr)

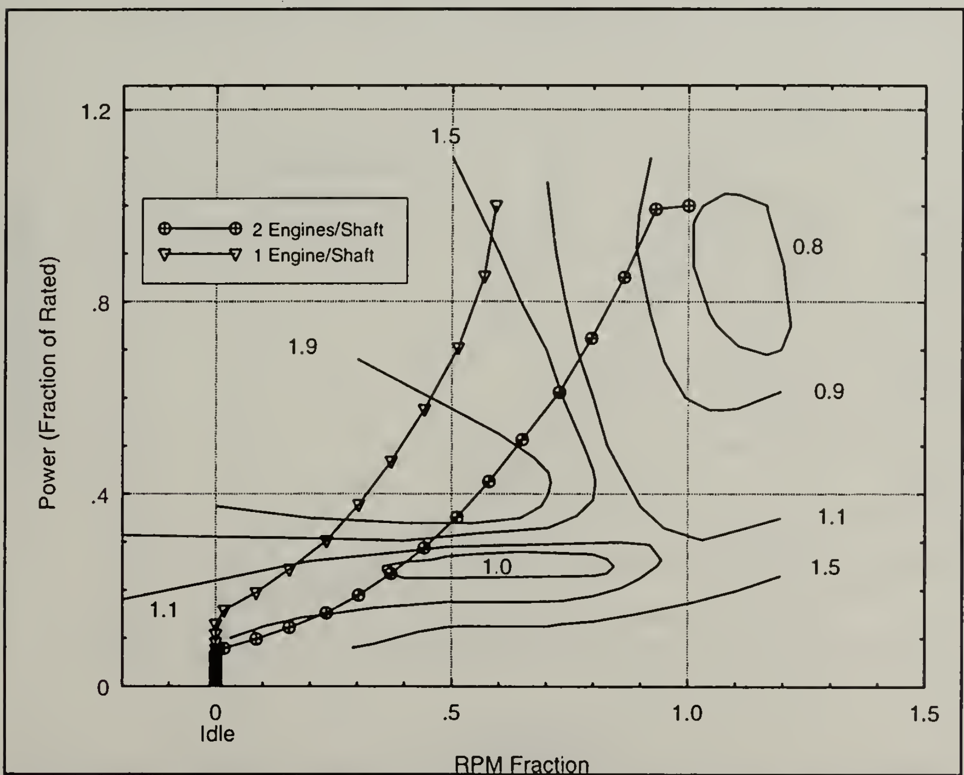


Figure 24: LSD 41 MPE CO Emission Contour Map (g/bhp-hr)

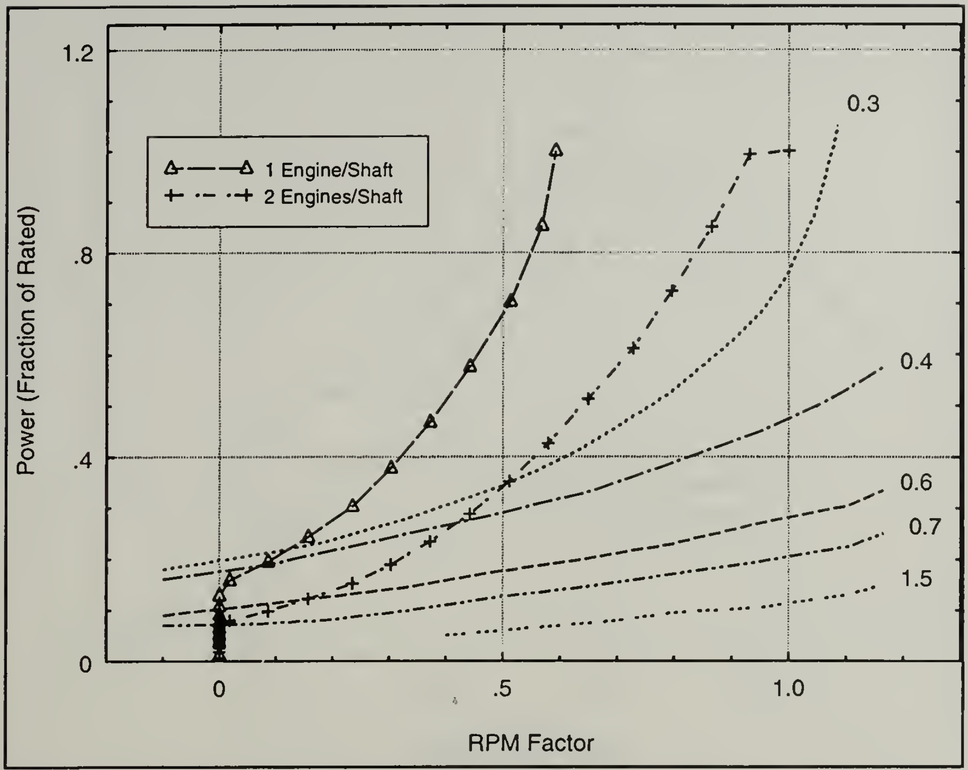


Figure 25: LSD 41 MPE HC Emission Contour Map (g/bhp-hr)

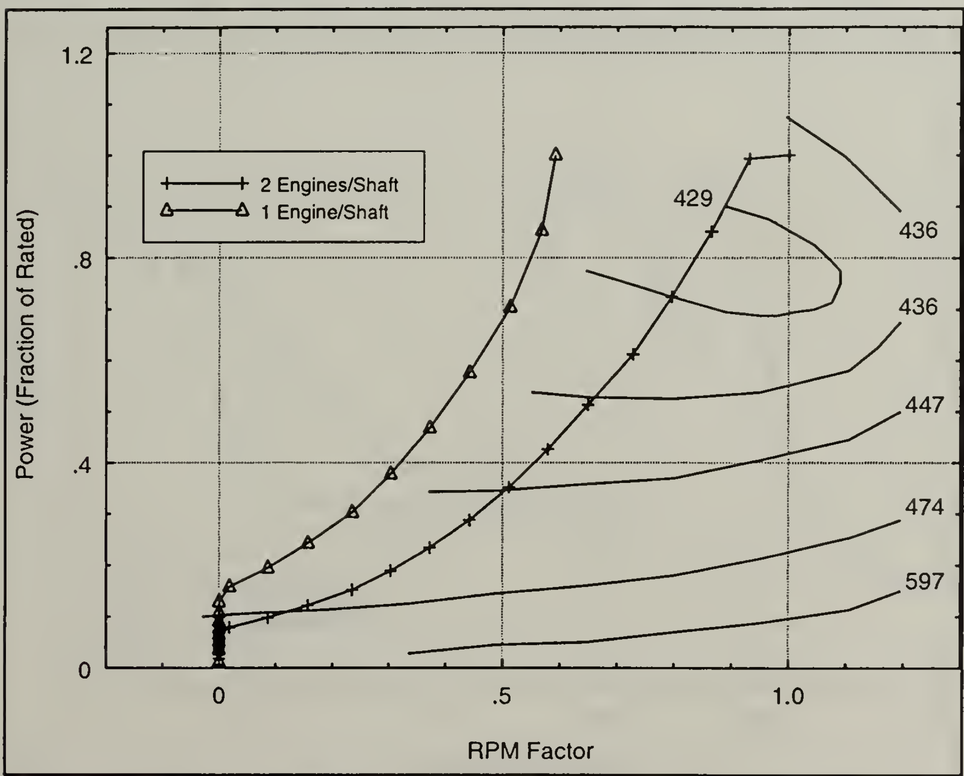


Figure 26: LSD 41 MPE CO_2 Emission Contour Map (g/bhp-hr)

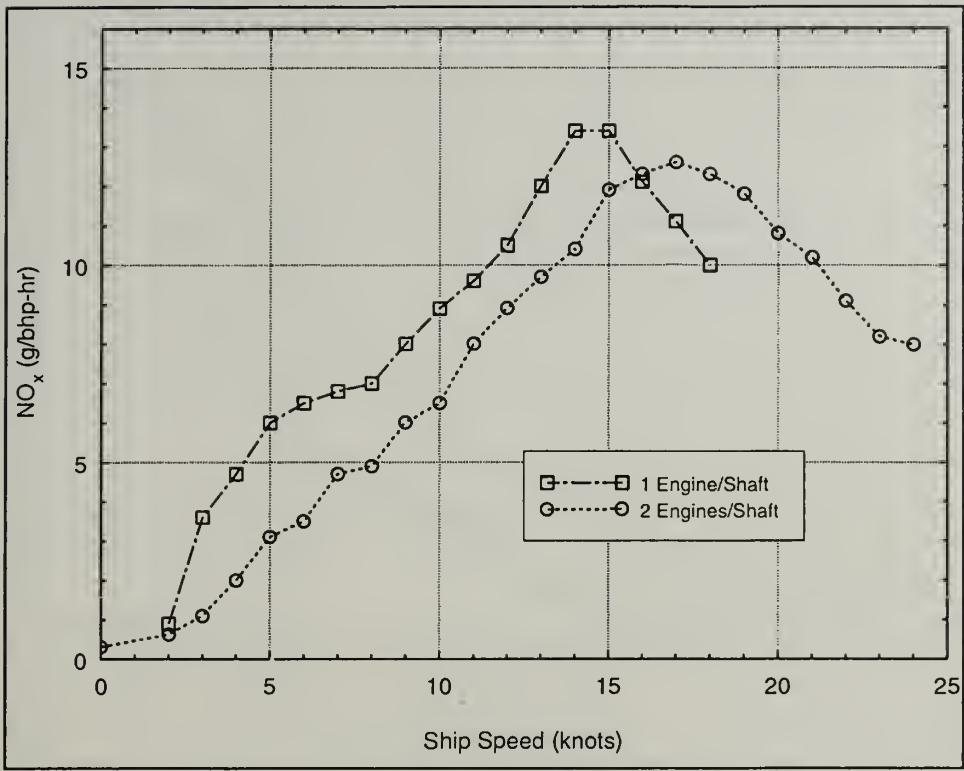


Figure 27: LSD 41 Class Speed vs. NO$_x$ Emissions

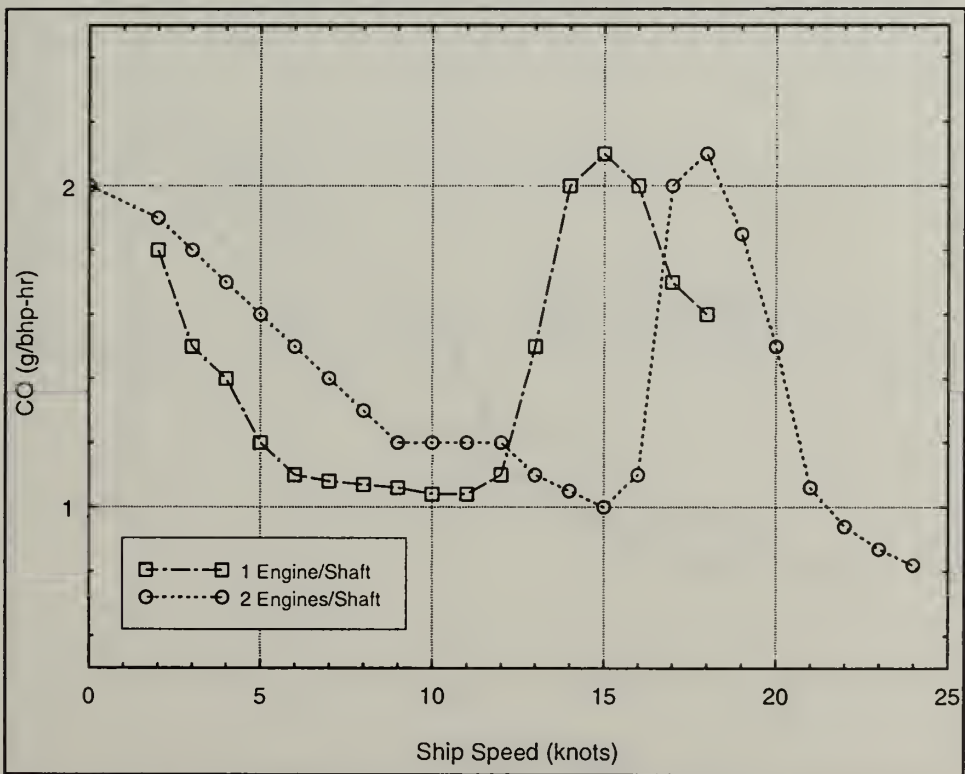


Figure 28: LSD 41 Class Speed vs. CO Emissions

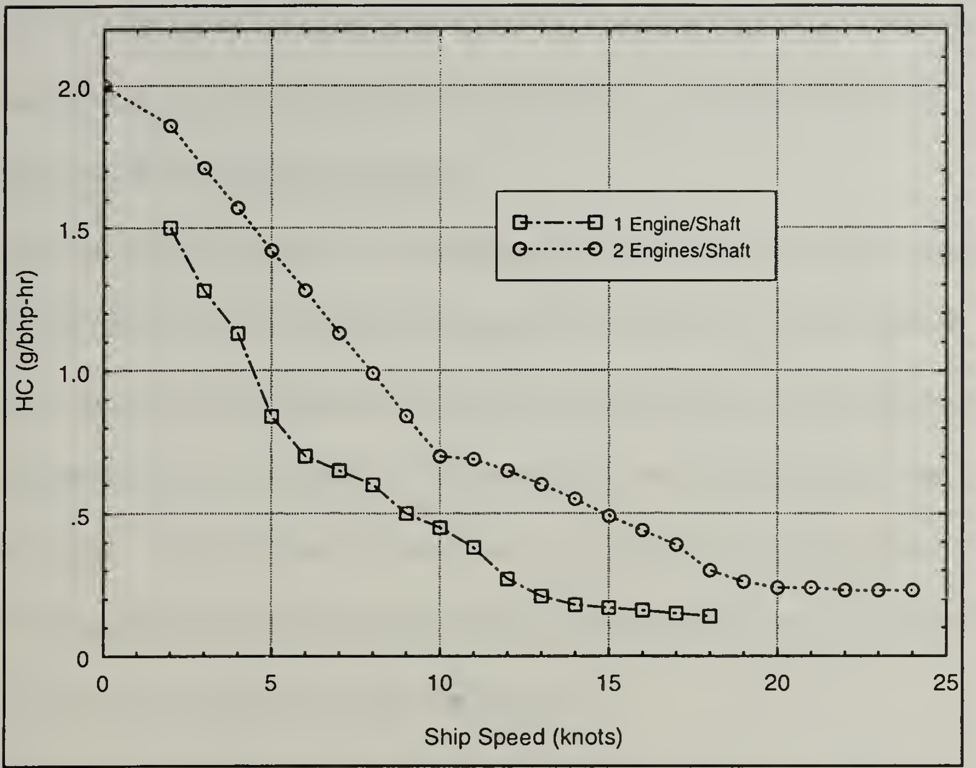


Figure 29: LSD 41 Class Speed vs. HC Emissions

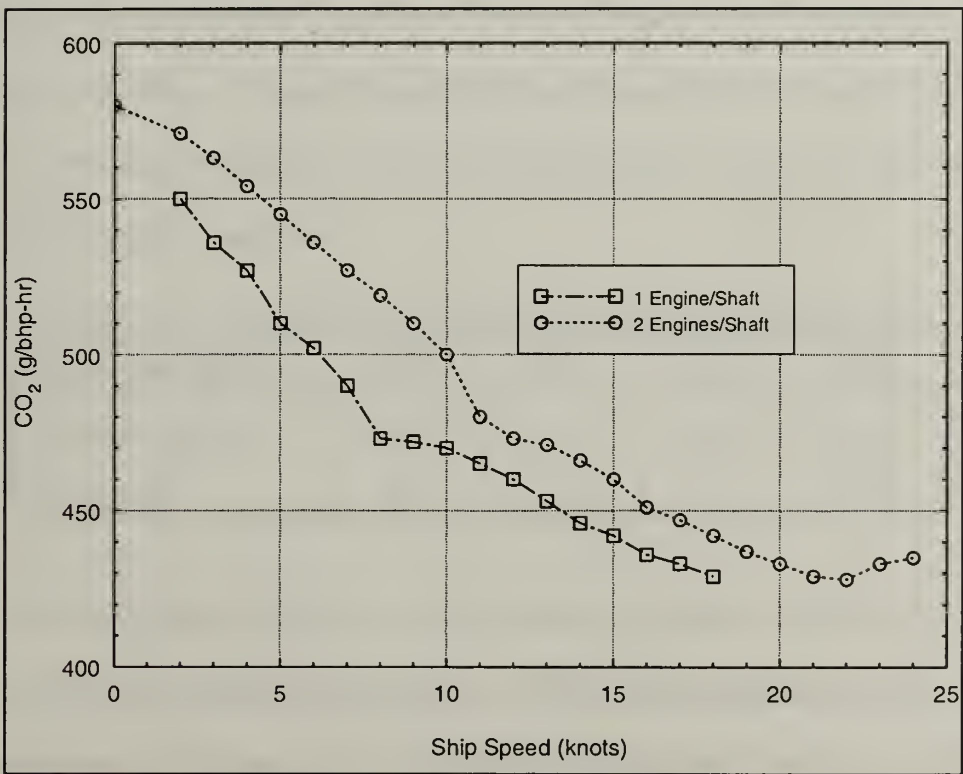


Figure 30: LSD 41 Class Speed vs. CO_2 Emissions

coincidence. 17 knots is the design endurance speed for most U.S. Naval ships. Therefore, by the curve of Figure 27, maximum NO_X production occurs at or near ship speeds used with highest frequency.

The curves of Figures 27 to 30 show the effect of reduced engine output on specific emissions. The plots of one and two engines per shaft indicate power required for specific speed. Figure 27 shows that NO_X levels decrease for lower engine loads. For example, at 15 knots the one engine/shaft curve indicates higher NO_X production than the two engines/shaft configuration. However, two engines/shaft increases both fuel consumption and the production of CO, HC and CO_2 emissions (Figures 28 to 30).

LSD 41 Class MPE Duty Cycle modes listed in Table 3-3 were next superimposed on the emission contour maps and engine specific brake emissions calculated. These emission contour maps appear in Appendix C. Table 4-1 provides the resulting LSD 41 Class propeller curve and LSD 41 Class Duty Cycle emission predictions.

Table 4-1: LSD 41 Class Emission Predictions (g/bhp-hr)

Prediction Method	NO_X	CO	HC	CO_2
Propeller Curve	8.5	1.5	0.6	475
Duty Cycle	8.3	1.5	0.7	483

Data presented in Table 4-1 shows strong correlation between the propeller curve and duty cycle predictions. Differences between emission values are of the order two percent and deemed negligible. Section 4.3 provides

a comparison with industry standards and emissions predictions for the T-AO 187 Class.

4.3 MPE Duty Cycle Comparison

The comparison was conducted by plotting the duty cycles presented in section 1.6 on the emission contour maps. Figure 31 provides a graphical description of the LSD 41 Class and seven industry duty cycles studied in this section. The speed/power points plotted represent each duty cycle described using equations 16 and 17.

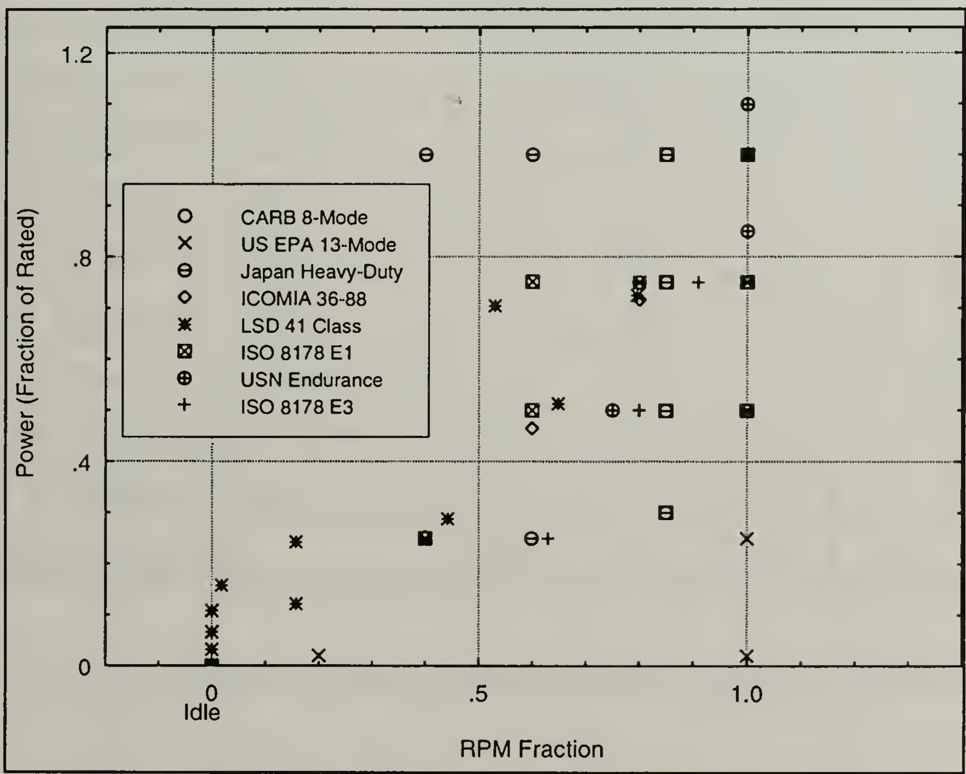


Figure 31: Duty Cycle Speed/Power Points

Comparison method is identical to that discussed in section 4.2. Appendix C contains the emission contour plots for the seven duty cycles

evaluated and the T-AO 187 Class comparison. The *Lotus 123W* spreadsheet used to calculate duty cycle emissions predictions is also given in Appendix C. Table 4-2 provides the MPE duty cycle comparison. Figures 32 to 36 illustrate the comparison graphically. Included in Table 4-2 is the Japanese NO_X prediction given by the curve of Figure 3. Values for NO_X predicted by the Japanese method are much greater than those predicted by the emission contour map method. However, excellent correlation exists between

Table 4-2: MPE Duty Cycle Emission Prediction Summary (g/bhp-hr)

Method	NO_X	J. NO_X	CO	HC	CO_2
LSD Class Propeller Curve	8.5	15.9	1.5	0.6	475
LSD Class 11-Mode Duty Cycle	8.3	15.9	1.5	0.7	483
ISO 8178-4 E3 Duty Cycle	9.9	14.4	1.0	0.3	433
ISO 8178-4 E1 Duty Cycle	6.9	16.3	1.6	1.0	499
ICOMIA 36-88 Duty Cycle	6.9	16.2	1.5	1.0	499
Japanese Heavy-Duty Diesel Cycle	9.9	15.9	1.2	0.4	444
U.S. EPA 13-Mode Duty Cycle	7.3	15.4	1.5	1.0	497
CARB 8-Mode Duty Cycle	9.1	14.6	1.1	0.5	452
U.S.N. Endurance Test	7.7	14.3	1.0	0.4	444

the two LSD Class methods demonstrating the validity of operating profile time factors.

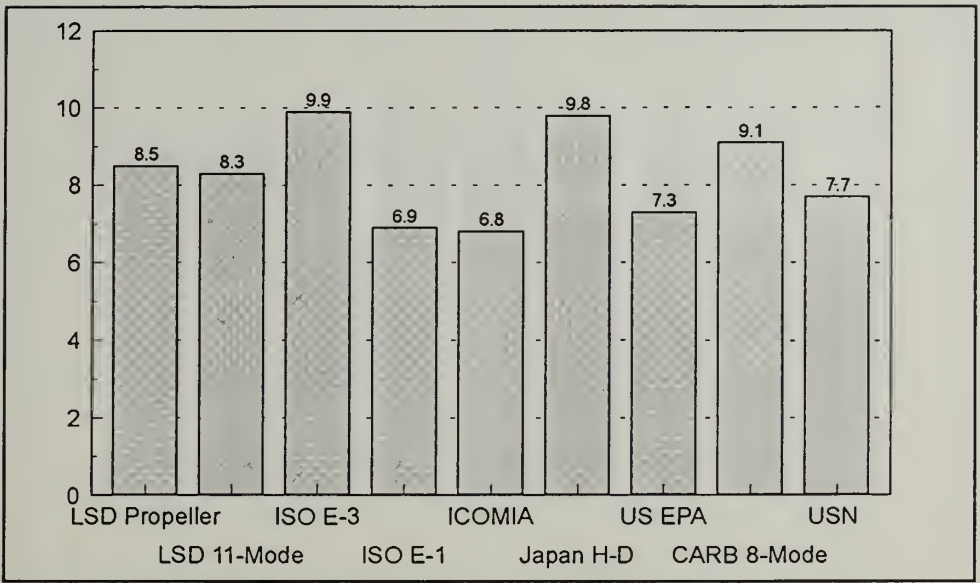


Figure 32: MPE NO_X Prediction Comparison (g/bhp-hr)

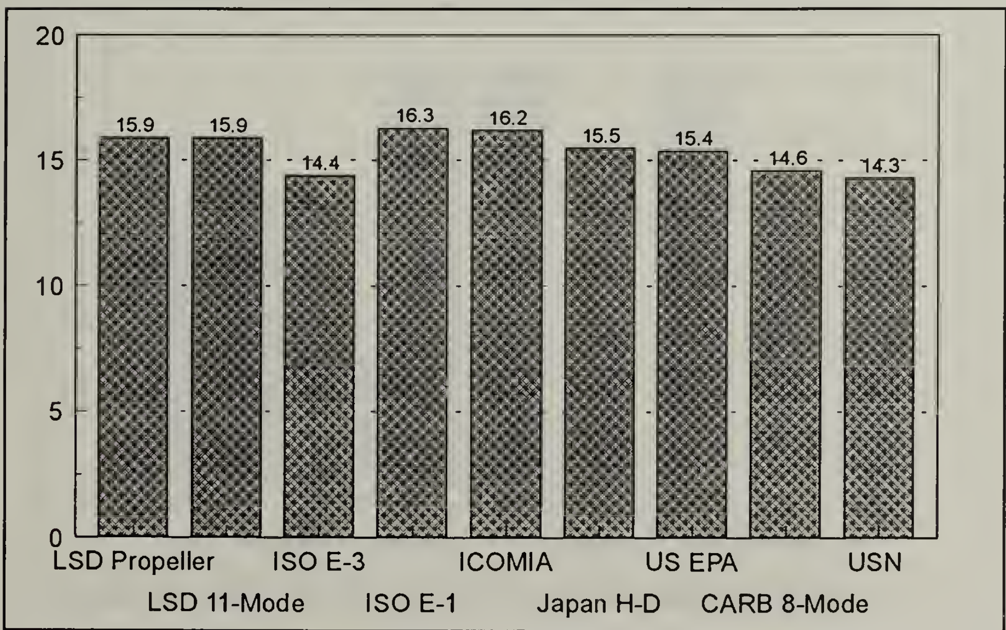


Figure 33: MPE Japanese NO_X Prediction Comparison (g/bhp-hr)

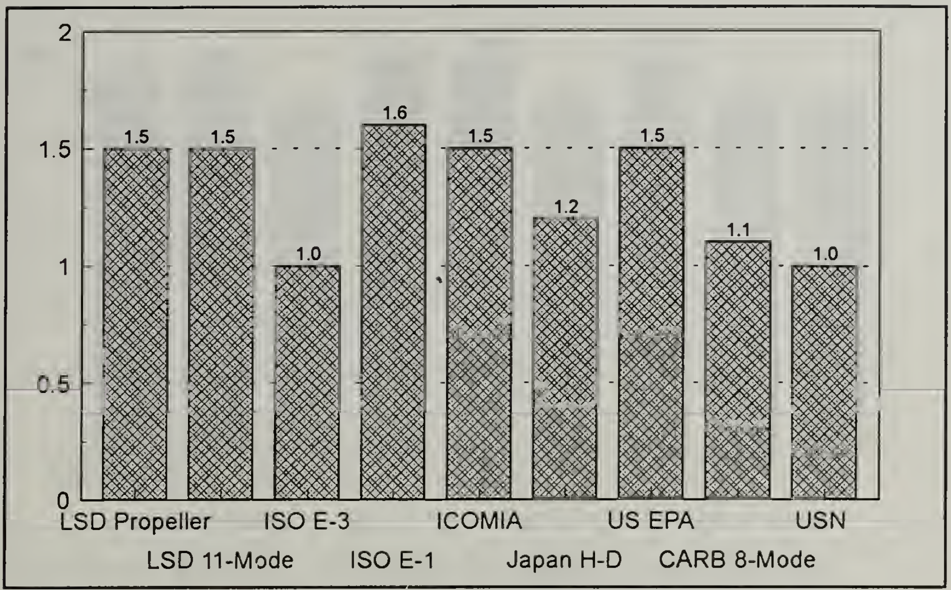


Figure 34: MPE CO Prediction Comparison (g/bhp-hr)

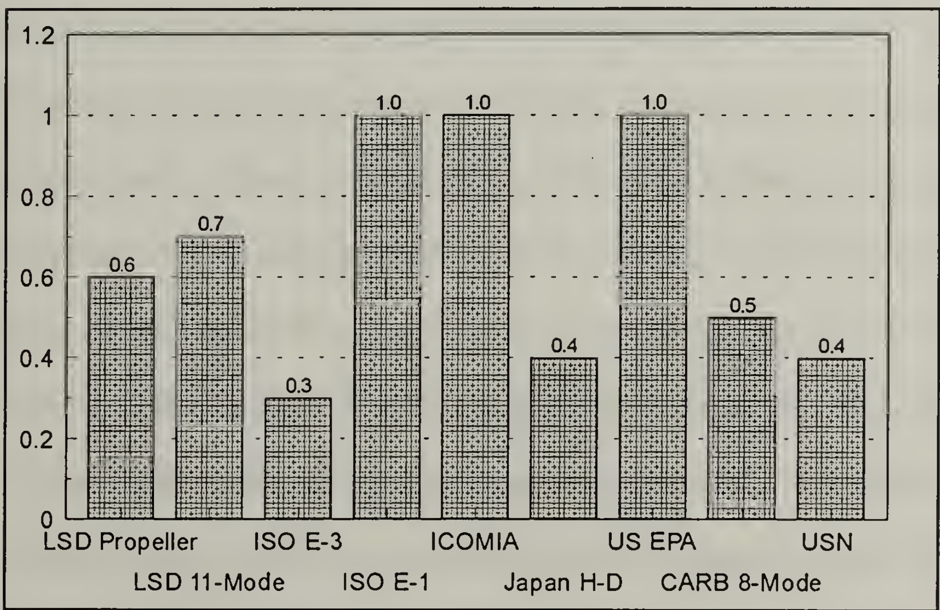
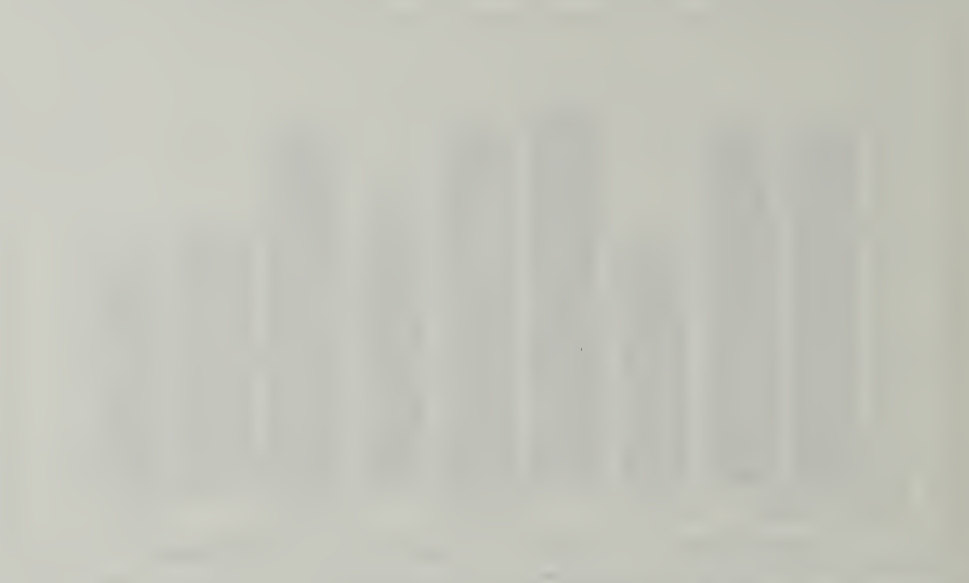


Figure 35: MPE HC Prediction Comparison (g/bhp-hr)



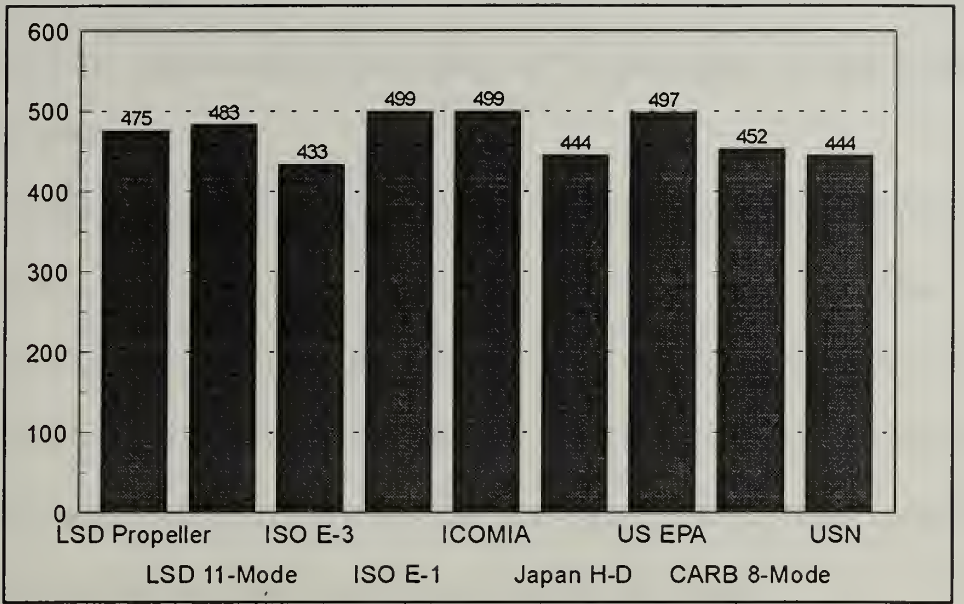


Figure 36: MPE CO_2 Prediction Comparison (g/bhp-hr)

Comparison charts of Figure 32 to 36 show duty cycle variation between emission predictions. In all five figures, the LSD 41 Class 11-Mode Duty Cycle provided the closest comparison to the LSD 41 Class Propeller Curve. The CARB 8-Mode Duty Cycle gives the next best NO_X comparison at 0.6 g/bhp-hr greater than propeller curve prediction (Figure 32). The ICOMIA 36-88 Duty Cycle calculates the second best Japanese NO_X Prediction at 0.3 g/bhp-hr over the propeller curve (Figure 33). CO predictions provided by the LSD 41 Class Propeller Curve, LSD 41 Class 11-Mode Duty Cycle, ICOMIA 36-88 Duty Cycle, and U.S. EPA 13-Mode Duty Cycle are the same (Figure 34). The CARB 8-Mode is second best in predicting HC emissions at 0.1 g/bhp-hr below the propeller curve (Figure 35). For CO_2, the U.S. EPA 13-Mode Duty Cycle follows the LSD 41 Class 11-Mode Duty Cycle at 22 g/bhp-hr over the value of the

propeller curve (figure 36). In short, no single duty cycle offers the consistency of the LSD 41 Class 11-Mode Duty Cycle in predicting LSD 41 Class engine exhaust emissions.

Plotting the propeller curve and calculated duty cycle for the T-AO 187 Class gives similar correlations. Table 4-3 provides the T-AO 187 Class emission predictions. Comparison with the charts of Figures 32 to 36 shows that no other duty cycle approaches the derived T-AO 187 Class 6-Mode Duty Cycle in predicting overall engine emissions for the ship operating profile. Appendix C contains the emission contour plots for the T-AO 187 Class.

Table 4-3: T-AO 187 Class MPE Emission Predictions (g/bhp-hr)

Prediction Method	NO_X	CO	HC	CO_2
Propeller Curve	7.6	1.4	0.8	482
Duty Cycle	7.7	1.5	0.8	483

4.4 SSDG Duty Cycle Comparison

The SSDG Duty Cycle comparison used emission data generated by Fairbanks Morse for engine 38D880013DGN12 on 30 May 1980. Though the same basic engine as the LSD 41 Class SSDG (38ND8-1/8, 12 cylinder opposed piston diesel engine), the engine tested was run with increased exhaust back pressure and no blower bypass valve. The test was performed on the engine as configured for use on *OHIO* (SSBN 726) Class submarines. Figure 37 provides the emission data for this engine. Constant speed data for no load condition was estimated based on relative comparison with the curves of Figures 19 to 21.

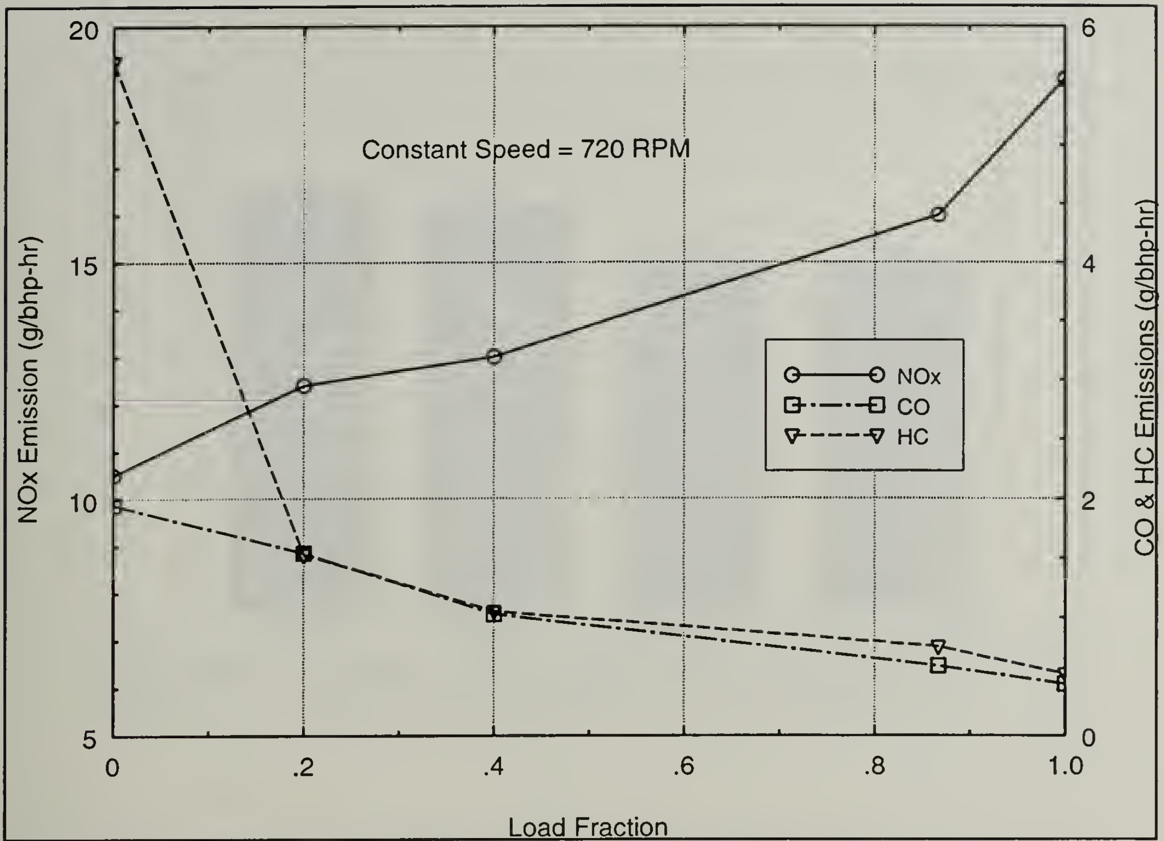


Figure 37: LSD 41 Class SSDG Exhaust Emission Curves

The curves of Figure 37 were used to determine emission data for the three industry constant speed duty cycles and the LSD 41 Class SSDG Duty Cycle. Summary emission data for the four duty cycles appears in Table 4-4.

Table 4-4: SSDG Duty Cycle Emission Prediction Summary (g/bhp-hr)

Prediction Method	NO_X	J. NO_X	CO	HC
DEMA Duty Cycle	16.4	14.0	0.6	0.7
ISO D1 Duty Cycle	16.0	14.0	0.7	0.8
ISO D2 Duty Cycle	13.7	14.0	1.0	1.3
LSD 41 Duty Cycle	13.6	14.0	0.9	1.1

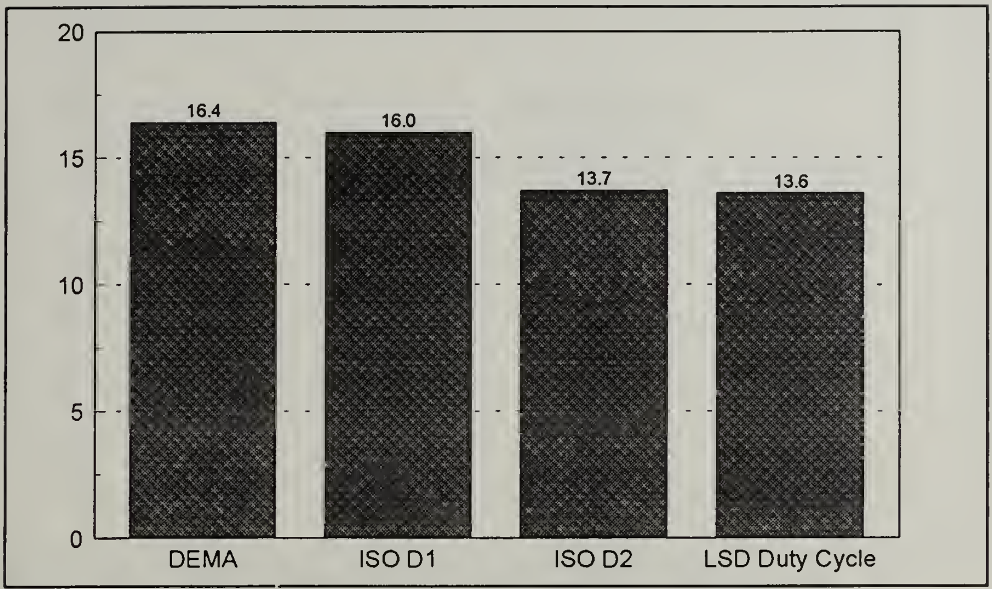


Figure 38: SSDG NO_X Prediction Comparison (g/bhp-hr)

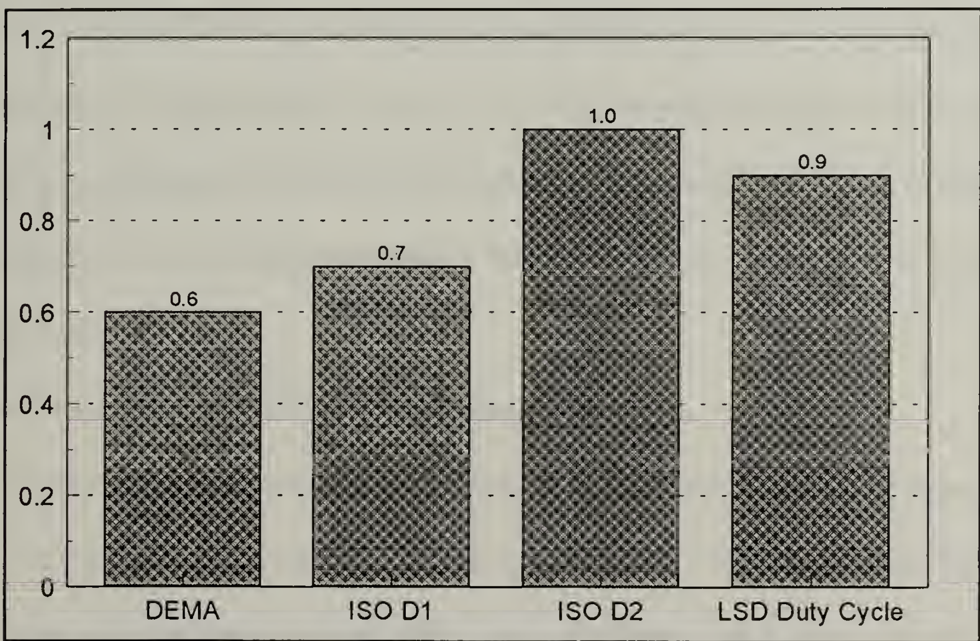


Figure 39: SSDG CO Prediction Summary (g/bhp-hr)

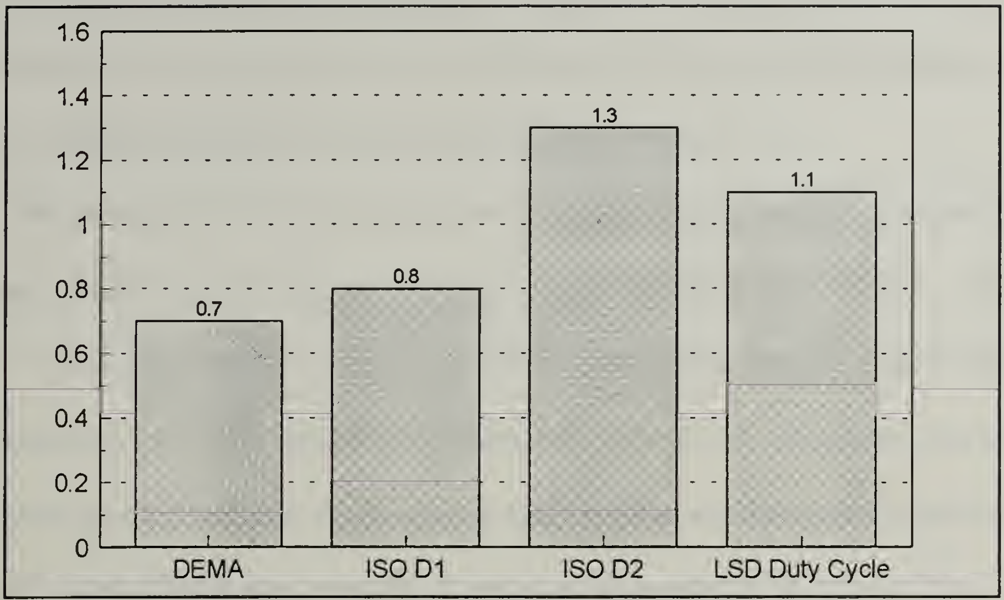


Figure 40: SSDG HC Prediction Comparison (g/bhp-hr)

The graphs of Figures 38 to 40 clearly indicate that the DEMA and ISO 8178-4 D1 Duty Cycles are inappropriate for modeling LSD 41 Class SSDG operation. ISO 8178-4 D2 provided the closest approximation to that calculated using the LSD 41 Class SSDG Duty Cycle. The identical prediction for NO_X made by the Japanese Formula was surprising. The observed range of engine speed values and time factors adding to the identical emission value is most probably coincidental.

4.5 Duty Cycle Conclusions and Applications

A duty cycle must provide an accurate correlation/prediction of actual emissions performance over some range of operation. The range of operation will include different applications that must be modeled individually. To facilitate the ship design process, a two step procedure for engine emission certification is

proposed. First, prequalify the engine at the same time the Endurance Test is performed by measuring emissions at Endurance Test speed/power points. Second, certify the engine after matching engine to hull form.

Naval ship designers choose main propulsion engines from a list of those that have passed the endurance test and receive certification. Table 4-2 and Table 4-3 indicate that the U.S.N. Endurance Test points provide a reasonable approximation of engine emission performance for LSD 41. However, the best duty cycle for emissions is not the same one for wear and endurance testing. To facilitate naval ship design candidate diesel engines should continue to be tested via Military Specification MIL-E-23457B for endurance and wear. Engine emission measurements should be taken concurrently. The U.S.N. Endurance Test continues for 1,000 hours offering ample time to measure engine emissions under steady state conditions. The emissions test procedure should follow the guidelines of ISO 8178. Concurrent emission measurement done in this manner should not present a burden to the engine manufacturer.

Emission data derived from the Endurance Test would form the basis for engine certification by the Navy. After marrying a specific hull design with a certified engine, emission prediction refinement, using the procedure of Figure 18, would be required. The environmental impact statement prepared by the ship program manager should reflect the refined emission prediction. Figure 41 illustrates the procedural steps for qualification of a diesel MPE for use on a specific new naval vessel design. Existing naval ship MPE's should be tested at

speed/power points and time factors derived from Figure 18, using ISO 8178-2 for procedural guidance.

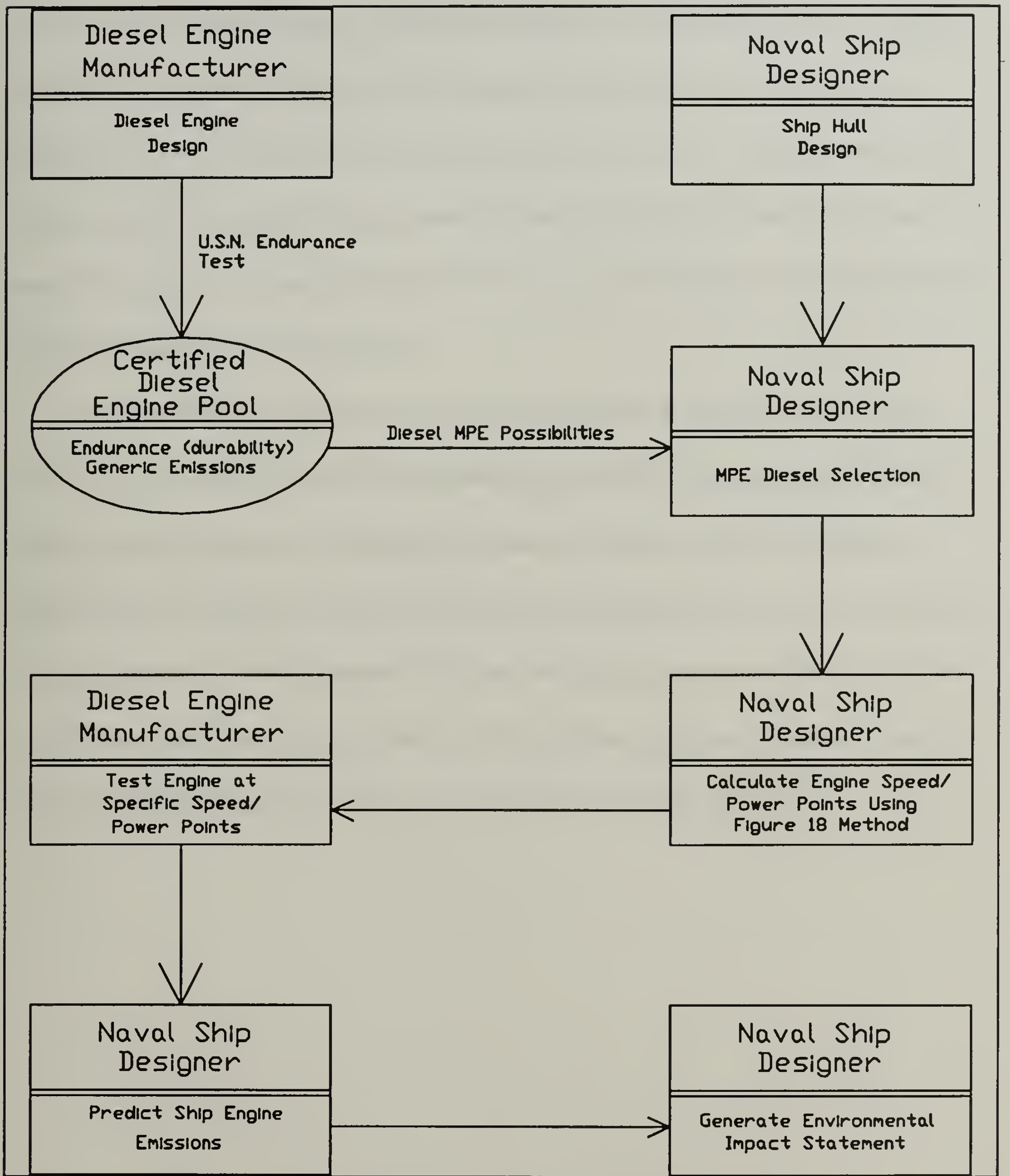


Figure 41: New Ship Design MPE Emission Certification Process

Ship service diesel engines should be exhaust emission pre-qualified and final emission certified using a procedure similar to that illustrated in Figure 41. In the case of constant speed diesel generators, it is probable that a modified ISO 8178-4 duty cycle D2 could be adopted by the Navy for final emission certification. The time factors (weight factors) of D2 can be readily modified to match actual ship operation by cursory review of the ship's Electrical Division logs. Procedural guidance of ISO 8178-1 for bench testing and ISO 8178-2 for shipboard testing should be used.

The method advocated in the California Federal Implementation Plan (CFIP) to calculate NO_X based solely on engine speed is oversimplified to the point of presenting grossly inflated estimates of engine exhaust emission performance. Tables 4-2 and 4-4 indicate over estimations of up to 100 percent. The procedure given in Chapter 3 and the evaluation presented in this chapter provide a simple, yet accurate method for predicting engine emissions based upon the actual operating profile of naval diesel powered ships.

CHAPTER 5: STACK EMISSION MEASUREMENT

Within the engine exhaust stack chemical transformation of diesel engine exhaust gases may occur. The exhaust stack system is defined as the system through which engine exhaust gases pass from the engine turbocharger exit to the atmosphere. Chemical processes occurring within the stack are primarily dependent upon residence time and stack temperature. Residence time within the stack is determined by stack length and gas velocity. The analysis detailed in this chapter utilizes the LSD 41 Class stack design.

5.1 LSD 41 Class Stack Description

Each propulsion engine has two turbochargers. Exhaust from each turbocharger is combined into a common header. Headers from each engine are run to, and up, the port and starboard uptakes. In the uptakes, each header is connected to an exhaust silencer which reduces airborne noise from each engine. The outlet of the exhaust silencer is connected to an exhaust pipe which continues to the atmosphere. The exhaust system piping is composed of stainless steel piping with a wall thickness of 0.188 inches. It's inner diameter is 2.14 feet at the inlet and 2.97 feet at the exit. The stack is approximately 127 feet in length, with total flow head loss calculated as 0.40 psi. Figure 42 illustrates the plan view[25], and Figure 43 the profile view[26], of the LSD 41 Class stack for the starboard main propulsion engines (MPE IA & IB). Table 5-1

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[25]NAVSEA Drawing 835-4799873, p. 8.

[26]Ibid., p. 9.

provides the stack inlet and outlet conditions.[27]

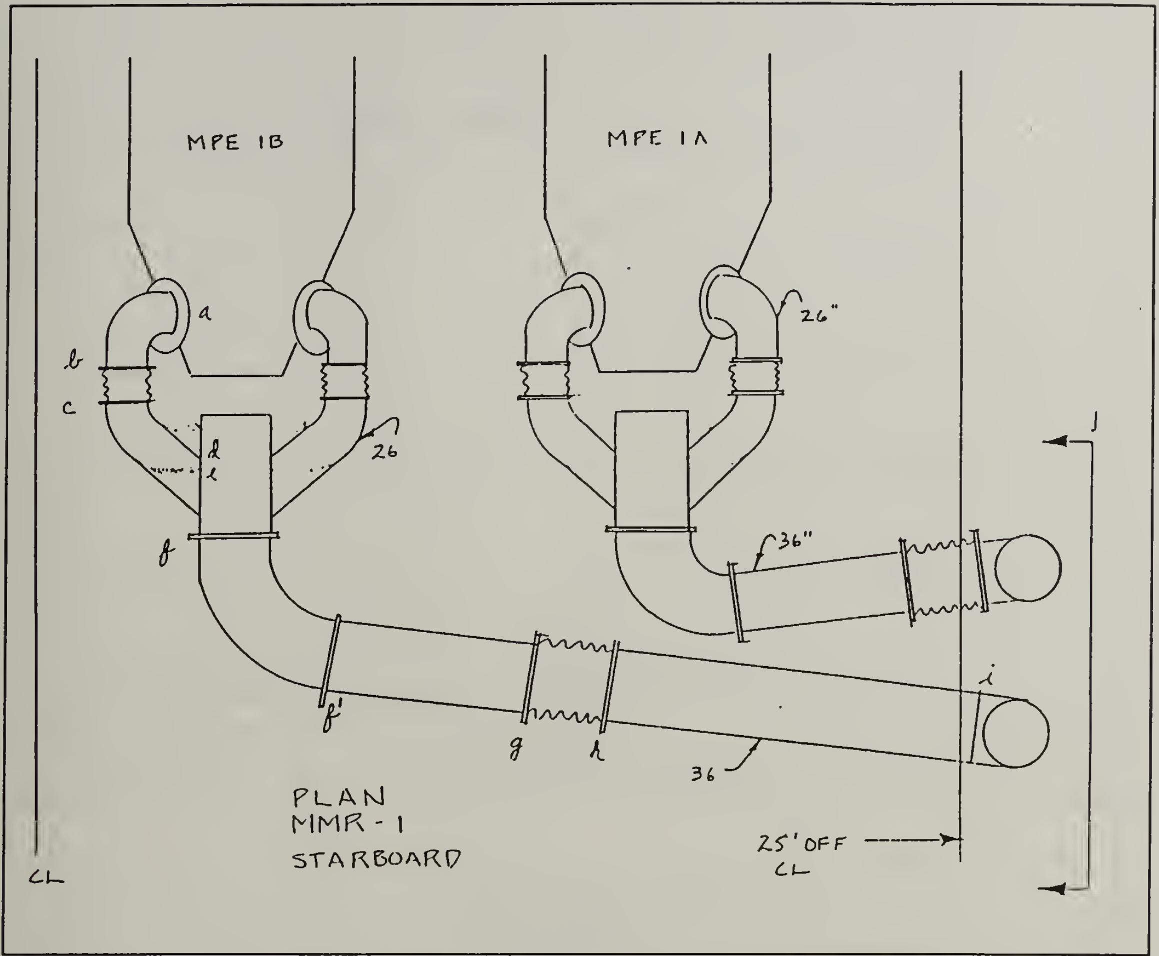

Figure 42: LSD 41 Class Starboard MPE Exhaust System - Plan View

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[27]NAVSEA Drawings 259-4799872 and 835-4799873.

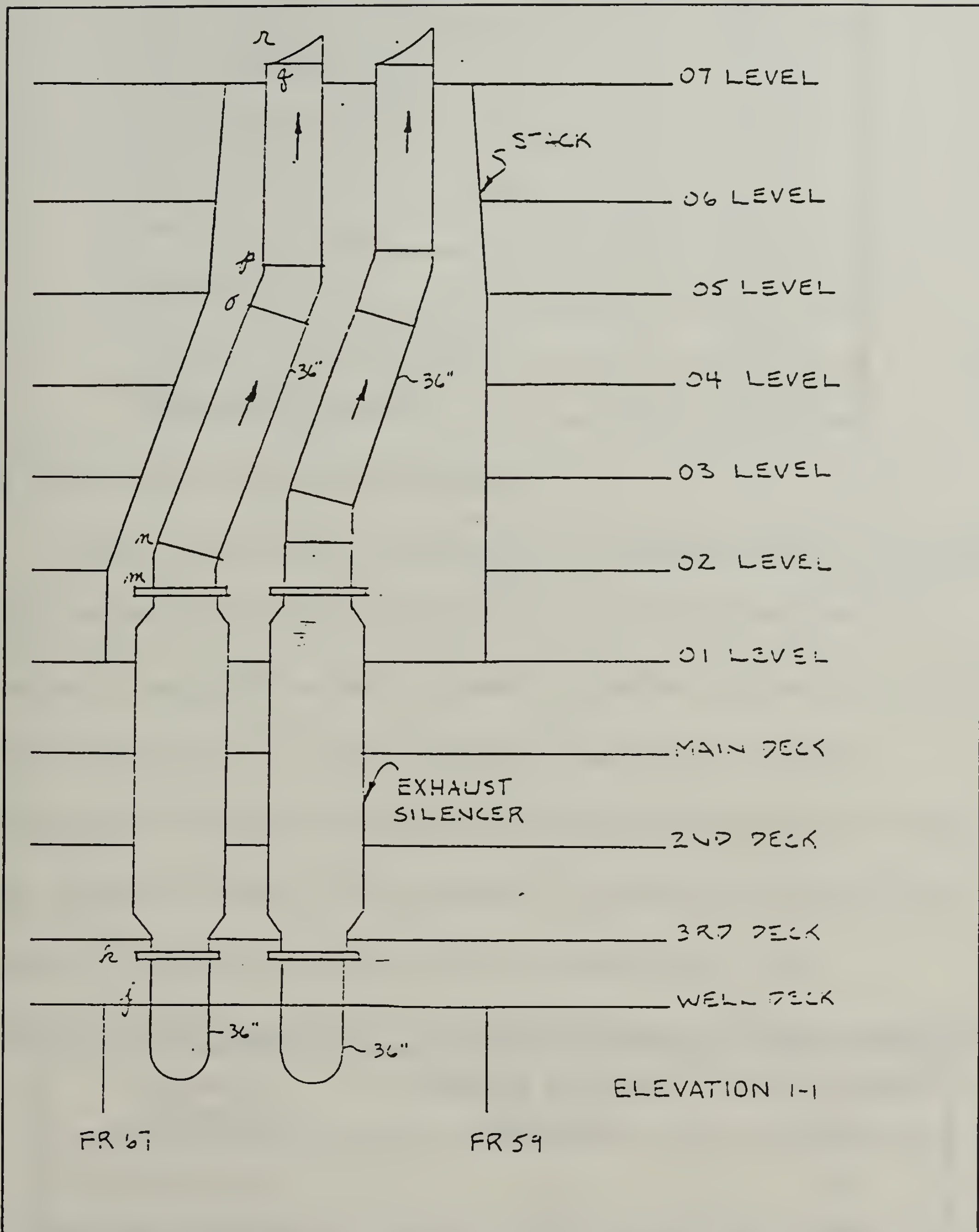

Figure 43: LSD 41 Class Starboard MPE Exhaust Stack - Profile View

Table 5-1: Exhaust Stack Flow Parameters

Parameter	Value
Inlet Temperature (^{O}K)	688.7
Exit Temperature (^{O}K)	688.7
Inlet Velocity (m/sec)	40.86
Exit Velocity (m/sec)	42.27
Inlet Pressure (psi)	25.0
Exit Pressure (psi)	24.6
Volume Flow Rate (m^3/sec)	1631.1
Residence Time (sec)	0.92

5.2 Exhaust Gas Constituent Analysis

Table 4-2 provided the 11-Mode LSD 41 Class Duty Cycle MPE exhaust specific emission predictions in units of grams per brake horsepower-hour. Analysis of chemical processes is facilitated by species represention in units of concentration (ppm). Conversion of specific emissions to volumetric concentrations requires specification of operating condition and time at that state. Operation at rated power and speed for one second was selected for analysis. Table 5-2 provides the gaseous emission levels studies.

Table 5-2: Colt-Pielstick 16 PC-2.5 V400 Emissions at Rated Conditions[28]

Gaseous Constituent	Specific Emission (g/bhp-hr)	Concentration (ppm)
Carbon Monoxide	0.8	155
Oxides of Nitrogen	9.0	1749
Hydrocarbons	0.2	39

[28]Letter dated 19 October 1993 from G. Monahan, Coltech Industries.

Table 5-2 data was then used to write the chemical equation describing the combustion of diesel fuel within the PC-2.5 engine at equivalence ratio of 0.38. Oxides of nitrogen were assumed to be made up of 90 percent NO and 10 percent NO_2. Equation 18 gives the chemical equilibrium condition for this combustion process.

$$C_nH_{1.8n} + 46.69O_2 + 177.18N_2 \rightarrow 12.02CO_2 + 0.04CO + 0.02C_nH_{1.8n} + \ldots$$

$$\ldots + 0.32NO + 0.05NO_2 + 1.98H_2O + 33.72O_2 + 177.00N_2 \qquad (18)$$

The hydrocarbon fuel, $C_nH_{1.8n}$, was approximated by $C_{12.3}H_{22.4}$ where n=12.3. This approximation was made since diesel fuel is a mixture of hydrocarbon compounds which have an overall molecular weight of approximately 170. For analysis purposes, the exhaust gaseous hydrocarbon was assumed to be made up of the chemical compounds listed in Table 5-3[29].

Table 5-3: Exhaust Gaseous Hydrocarbon Constituents

Family	%	Modeled As	Formula	# Moles (E-3)	Grams
Paraffins	36	Ethane	C_2H_6	5.7	0.171
Cycloparaffins	40	Cyclobutane	C_4H_8	3.91	0.219
Olefins	9	Propene	C_3H_6	1.00	0.043
Other	15	Not Modeled	*	0.00	0.000

The chemical compounds listed under "Other" in Table 5-3 consist of Indans and Tetralins (5%), Indene (1.3%), Naphthalene (4.4%), Acenaphthylene (4.0%), and

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[29]Gaseous hydrocarbon composition is consistent with Table 17 of Fossil Fuel Combustion A Source Book by William Bartok and Adel F. Sarofim, John Wiley & Sons, 1991, p. 43.

Tricyclicaromatics (0.3%). Due to their minor contribution to the overall compostion of diesel fuel, and limitations on the combustion model employed, "Other" hydrocarbons were not modeled.

Exhaust gas analysis was performed by using Sandia Labs computer software package *CHEMKIN* to model exhaust gas composition changes within the stack. *CHEMKIN* is a *FORTRAN* chemical kinetics code designed to facilitate simulations of elementary chemical reactions in flowing systems. *CHEMKIN* solves the stiff differential equations describing a particular set of boundary conditions and chemical species present. User inputs include: elements, species, Arrhenius reaction rate coefficients, boundary conditions and reaction time span. Arrhenius reaction rate coefficients describe the rate at which a chemical reaction takes place. For example, oxidation of carbon monoxide (CO) to carbon dioxide (CO_2) is given by Equation 19.

$$CO + O_2 \rightarrow CO_2 + O \qquad (19)$$

The rate at which carbon monoxide and oxygen react to form carbon dioxide is governed by the Arrhenius expression of the form of equation 20.

$$k = A T^{b} \exp\left(-\frac{E}{RT}\right) \qquad (20)$$

The reaction rate (k) is dependent upon activation energy (E), temperature (T), gas constant (R), and Arrhenius coefficients A and b. The reaction rate of Equation 19 is given by Equation 21.

$$k = 1.60E13 \times T \times \exp\left(\frac{-41{,}000}{1.987 \times T}\right) \qquad (21)$$

A in Equation 21 is in units of mole-cm-sec-K and E in units of cal/mole.

The *Intrepeter* program of *CHEMKIN* reads the symbolic description of the chemical reaction mechanisms to be studied. *Interpreter* then provides a linking file to the 100 module *Gas-Phase Subroutine Library*. This library returns information on equation of state, thermodynamic properties, and chemical production rates.[30] Appendix D provides the input file and interpreter file which lists the chemical reactions and species studied.

Gas-Phase Subroutine solves the differential equations which describe chemical species rate of change. For example, the production of NO during the combustion process occurs by three principle means: thermal, prompt, and fuel-bound mechanisms. The thermal NO formation mechanism is the extended thermal or Zeldovich reaction system of equations. NO formation at temperatures above 1000° K increases exponentially; but at lower temperatures the reaction rate is very slow. Equations 22 to 24 give the Zeldovich reaction scheme.

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[30]Robert J. Kee, et. al., "CHEMKIN-II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics," Sandia National Laboratories, December 1990, pp. 3-10.

$$O + N_2 \rightleftharpoons NO + N \qquad (22)$$

$$N + O_2 \rightleftharpoons NO + O \qquad (23)$$

$$N + OH \rightleftharpoons NO + H \qquad (24)$$

Estimation of NO concentration requires knowledge of the temperature and concentrations of other species. Analysis is simplified by assumption of equilibrium conditions existing between the reaction products. Reaction rate constants for forward and reverse reactions of Equations 22 to 24 must be known in order to determine the change in NO concentration over time. The rate change of NO concentration is given by Equation 25.

$$\frac{d[NO]}{dt} = 2k_{22}[O][N_2]\frac{1 - \dfrac{[NO]^2}{K_e[O_2][N^2]}}{1 + \dfrac{k_{-22}[NO]}{k_{23}[O_2] + k_{24}[OH]}} \qquad (25)$$

Where K_e is the equilibrium constant for the production of NO from the oxidation of atmospheric nitrogen (N_2) by oxygen (O_2). The reaction coefficients are given in Fundamentals, Modeling and Computations in Reacting Flows and Combustion, by A. F. Ghoniem, 1993, p. 2-41.

Exhaust gas flow reactions were modeled by 164 reaction mechanisms involving 38 chemical species. Several assumptions were made to simplify the analysis:

1. High volume flow rate and low residence time in the stack minimize heat transfer between gas flow and stack piping. Therefore, adiabatic constant

enthalpy conditions were assumed.

2. The gas stream was modeled as a well stirred reactor due to the significant amount of mixing occuring post combustion.

3. The gas was modeled as a plug flow system allowing Lagrangian description.

4. Species listed in Table 5-3 and Appendix D were appropriate for modeling the gaseous unburned diesel fuel.

5. Particulate emissions were assumed to be inert. Therefore, chemical reactions between gaseous species and particulate matter were ignored.

Results of the *CHEMKIN* model are displayed in Figure 44. It is readily apparent that the low temperature within the flow, 688.7°K, and short residence time of 0.92 seconds was insufficient to allow significant oxidation of unburned gaseous hydrocarbon. Reactivity of the species in the exhaust stream, as modeled by the Arrhenius chemical reaction rate coeficients, were insensitive to the temperature within the stack. NO_x concentrations, as well as all others, were frozen at exhaust manifold levels.

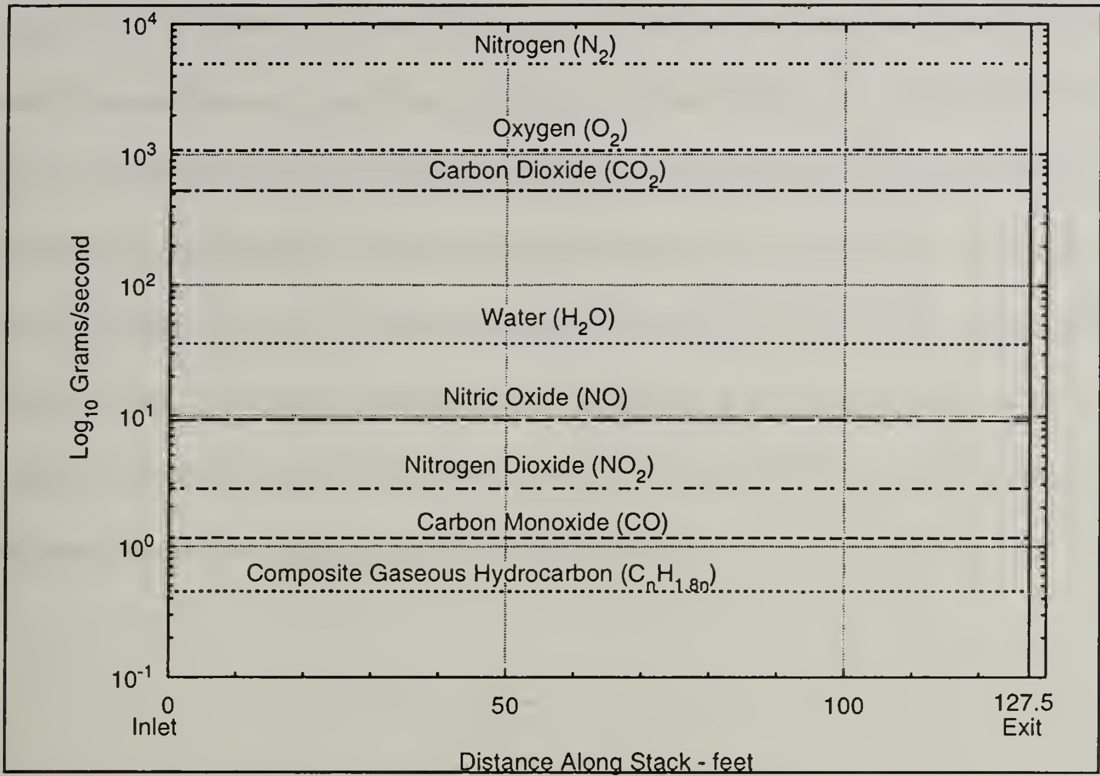

Figure 44: ***CHEMKIN*** **Exhaust Stack Model**

5.3 Ship Emission Measurement

Figure 44 shows gaseous concentrations do not change significantly within the exhaust stack; in fact exhaust stack chemistry is frozen at inlet concentrations. The LSD 41 Class is well suited for engine exhaust emission measurement. Engine operating console in each main machinery room provides analog output of: engine RPM, shaft torque, shaft RPM, fuel flow rates, and engine temperatures and pressures.

Instrumentation of the inlet plenum and exhaust stack would be required to determine gas flow parameters. Inlet gas conditions may be modeled by turbocharger performance. Exhaust measurements may be taken where most

convenient. Exhaust measurement at turbocharger and stack exit locations are readily accessible and could be used with minimum impact on ship operations. Existing inspection covers could be modified to accept the sampling probe, or special boss type fittings installed in the stainless steel piping itself. Portable gas analyzers, such as the ENERAC 2000E used during the USCG cutter *Point Turner* testing, offer data collection and analysis in a compact format. Data collecting should be performed to simultaneously record ship propulsion plant parameters and resulting engine emission levels.

Chapter 6: Conclusions and Recommendations

The U.S. Navy, Naval Sea Systems Command Code 03X3, published *Internal Combustion (Gas Turbine and Diesel) Engine Exhaust Emission Study* in 1991. On page 6-1 of this study, the following observation is made: "Before the Navy can begin an emission test program it must decide the test points for which to collect emission data..." This thesis recommends a methodology for determining the test points for diesel powered ships.

Log review, used in preparing this thesis, offers a method to develop ship operating profiles which formed the basis for developing engine duty cycles. This approach expended approximately 600 man-hours. Although this method provided reasonable and consistent results it is recommended that NAVSEA instrument two LSD 41 Class ships (one on each coast) to validate the operating profile derived by log review. Ships should be instrumented for six months and should include emission measurements taken at convenient intervals. These measurements could be used to confirm the emission estimates developed in this thesis. After validation, operating profiles and emission estimates for other naval diesel ship classes should be derived by log review and prediction methods developed in this thesis. Engine exhaust emissions should be calculated for each ship type. Following ship emission determination, comparison with emission limits can be made and strategies for ship engine emission reduction studied for their interdependence and effect on naval ship operations.

CARB proposed NO_X emission limits for existing diesel powered ships is 600 ppm. U.S. Naval vessels are currently exempt from this policy. Future regulations may require naval ship compliance. Development of specific engine emission contour maps requires many hours of costly engine operation on the test stand. NO_X emission concentrations of 565 ppm over a 24 hour period were predicted in this research using the LSD 41 Class Duty Cycle and generic engine emission contour plots. Determination of actual Colt SEMT-Pielstick PC2.5 V400 diesel engine emissions at LSD 41 Class Duty Cycle points is recommended to certify LSD 41 Class emissions.

Industry standard duty cycles of ISO 8178-4, EPA and others were shown to be inadequate for estimation of naval ship engine exhaust emissions. The Navy should present the method outlined in Chapters' 3 and 4 to national and international regulatory organizations and classification societies (such as EPA, CARB, ISO, IMO, etc...) for adoption. In addition, the Navy should formalize the conclusions presented in Section 4.5 by adding them to Military Specification MIL-E-21260D, *Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed*, and its sister document for high speed diesel engines. The certification method advocated in this thesis is applicable to both MPE and SSDG engines.

Chemical kinetic computer routines, such as *CHEMKIN*, are useful in predicting chemical composition of diesel engine exhaust. Analysis indicated exhaust gas emitted from the stack is similar to that exiting the engine. Interaction between gaseous and particulate material, and particulate behavior

in the stack, is not well defined nor understood; therefore, further research is warranted. This can be accomplished in three ways: in the lab, through instrumentation of ship exhaust stack, or through use of more sophisticated computer codes possessing the ability to model a greater number of gaseous and particulate species and reactions.

Future work should consider engineering remedies and cost benefit analysis to optimally reduce engine emissions. Possible solutions have been discussed in Section 1.4. However, each solution may have an impact on others. For example, reduced speed operation will lessen NO_X production, but will also reduce the exhaust flow bulk temperature. Selective Catalytic Reduction (SCR) methods rely on temperatures at or above 800° F. When operated by current doctrine, diesel engine exhaust temperatures are typically very near this temperature. Speed restriction would reduce exhaust flow temperature and therefore minimize the effectiveness of SCR. Other possible solution methods include the relocation of operating areas farther out to sea and implementation of designated transit lanes with near land speed restrictions. These solutions will have an impact on U.S. Navy operations. What seems a reasonable engineering solution to a given problem may be inadequate when viewed from the perspective of the ship operator. Complete analysis of the interaction between proposed solutions and associated costs must be performed.

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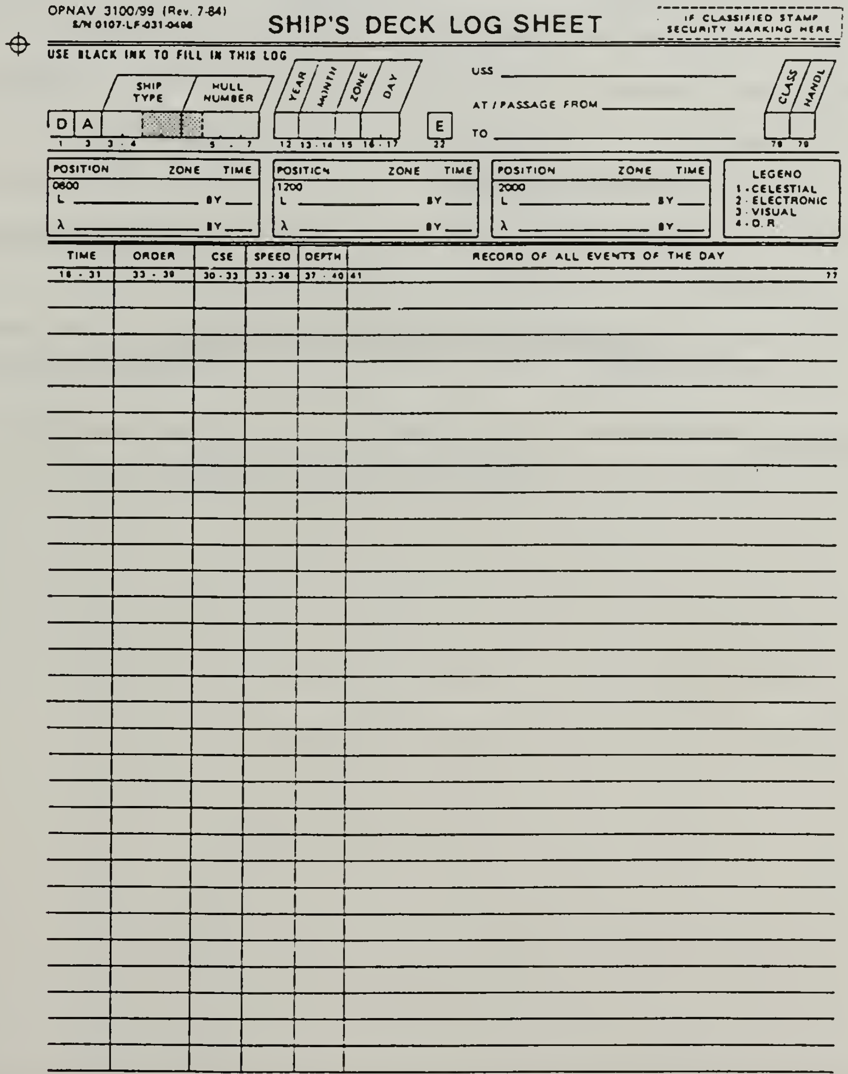
Appendix A: Sample Ship Log Data Sheets

This appendix contains blank sample ship log sheets representative of those reviewed to develop the LSD 41 Class operating profile described in Chapter 2.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SHIP'S DECK LOG SHEET

IF CLASSIFIED STAMP SECURITY MARKING HERE

USE BLACK INK TO FILL IN THIS LOG

SHIP TYPE | HULL NUMBER | YEAR | MONTH | ZONE | DAY | CLASS | HANDL

D A | E

USS

AT / PASSAGE FROM

TO

POSITION ZONE TIME	POSITION ZONE TIME	POSITION ZONE TIME	LEGEND
0800	1200	2000	1 - CELESTIAL
L BY	L BY	L BY	2 - ELECTRONIC
λ BY	λ BY	λ BY	3 - VISUAL
			4 - D. R.

TIME	ORDER	CSE	SPEED	DEPTH	RECORD OF ALL EVENTS OF THE DAY

Figure A-1: Ships Deck Log Sheet

ENGINEERING LOG
NAVSEA 3120/2B (REV. 10-81) S/N 0116-LF-031-2115 (9-77 EDITION IS OBSOLETE) CLASSIFICATION

U.S.S.					HULL NUMBER
DAY	MONTH	YEAR	TIME ZONE	TIME ZONE CHANGE TO	TIME ZONE CHANGE FROM
AT/PASSAGE FROM				PASSAGE TO	TOTAL MILES TRAVELED TODAY

EQUIPMENT STATUS *(Need not be completed for continuing pages)*

MAIN ENGINES	PLANT STATUS	BOILERS
GENERATORS	STEERING ENGINES COMBINATION	
DAYS OUT OF DRY DOCK	CATAPULT STATUS *(CV's Only)*	DAYS SINCE LAST HULL CLEANING
DRAFT FWD	DRAFT AFT	DRAFT MEAN	TONS
LIQUID LOAD	PERCENT OF FULL LOAD (%)	
MAJOR EQUIPMENT OUT OF COMMISSION		

EXAMINED DAILY AND CERTIFIED TO BE CORRECT

SIGNATURE OF ENGINEER OFFICER/RANK	DATE OF SIGNATURE

TIME	RECORD OF ALL EVENTS OF THE DAY	DAY	MONTH	YEAR

CLASSIFICATION PAGE NO.

Figure A-2: Engineering Smooth Log Sheet

Ship Service Diesel Generator 1 2 3 4						USS RUSHMORE (LSD 47) Engineering Operating Log											DATE			2 of 3
	TEMPERATURE																			
TIME	HOTTEST NO	CYLINDER TEMP	COOLEST NO	CYLINDER TEMP	S/W OVBD	SEA WATER FROM AIR COOLER	INJECT TEMP	ENGINE IN	JACKET WATER ENGINE OUT	JW COOLER OUTLET	L/O COOLER OUTLET	LUBE OIL ENGINE OUT	INLET COOLER	OUTLET COOLER	STATOR TEMP	FUEL SERVICE TANK LEVEL #1	FUEL SERVICE TANK LEVEL #2	ENGINE SUMP LEVEL	EXPANS TANK LEVEL	
0000																				
0100																				
0200																				
0300																				
0400																				
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2300																				
MIN								95	140	140	95	115	140	135		1240	1240	ADD	1/4	
MAX		730		730	130	130		185	185	175	185	185	195	170	100° C	2300	2300	FULL	3/4	

Figure A-3: Engine Operating Log Data Sheet

Appendix B: Ship Visit Summaries

This appendix provides summaries of ship, coast, and four ship cumulative MPE time factors supporting the LSD 41 Class Operating Profile development of Chapter 2. The data of Table 2-7 is repeated here for appendix completeness.

Table B-1: LSD 41 Class Ship Data Summary (All Times in Minutes)

	LSD 43	LSD 44	LSD 46	LSD 47
Name	Fort McHenry	Gunston Hall	Tortuga	Rushmore
Coast	West	East	East	West
Time Period (1993)	12 July 16 December	14 September 30 November	3 March 20 September	1 June 16 December
Main Propulsion Engine Data				
Data Points	5,011	2,816	4,267	3,013
Time Covered	252,324	133,052	159,845	145,517
Time Secured	74,589	54,499	76,872	51,025
Time Running	177,735	78,553	82,973	94,492
Time Warmup	1,458	1,306	1,892	1,571
Time @ Idle	2,886	1,725	2,357	1,155
Time @ Power	173,391	75,522	78,724	91,766
Ship Service Diesel Engine Data				
Data Points	992	414	862	809
Time Covered	239,750	146,895	210,854	182,942
Time Secured	66,127	38,516	90,442	55,328
Time Running	173,623	108,379	120,432	127,614
Time Warmup	1,602	1,664	2,101	3,065
Time @ Idle	1,039	4515	2,329	1,275
Time @ Power	170,982	106,300	116,002	123,274

The next five sections contain spreadsheet time summary sheet and graphic summaries for: each ship, by coast, and overall composite. The spreadsheet columns are mostly self explanatory. However, some explanation is required.

- The LSD 41 Class has four MPE's, numbers 1A and 1B on the starboard shaft, and 2A and 2B on the port shaft.

- The time values given are in minutes.

- "_n" indicates normalization to some value. Time values (i.e. 1A_n) are normalized to engine total time running. RPM and power are normalized to their rated values (520 and 8,500 respectively).

B.1: USS *FORT McHENRY* (LSD 43)

Table B-2: *USS FORT McHENRY* (LSD 43) MPE Data Summary

MPE Time Factor Calculations	IA	1A_n	1B	1B-n	2A	2A_n	2B	2B_n	Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Powor_n
Data Points:	1145		1345		1193		1328		5011							
Total Time:	56708		64687		62328		68601		252324							
Time Secured:	18916		14968		21660		19045		74589							
Time Running:	37792	1	49719	1	40668	1	49556	1	177735	1						
Time Warming Up:	298	0.008	341	0.007	328	0.008	491	0.01	1458	0.008						
Time at Idle:	783	0.021	652	0.013	794	0.02	657	0.013	2886	0.016						
Time at Power:	36711	0.971	48726	0.98	39546	0.972	48408	0.977	173391	0.976						
	298	0.008	341	0.007	328	0.008	491	0.01	1458	0.008			200	0.385	Warm	0
	783	0.021	652	0.013	794	0.02	657	0.013	2886	0.016			200	0.385	Idle	0
	997	0.026	821	0.017	1058	0.026	889	0.018	3765	0.021	All Stop	0	201	0.387	0	0
	369	0.01	369	0.007	351	0.009	348	0.007	1437	0.008	2	2	201	0.387	52	0.006
	15	0	18	0	24	0.001	13	0	70	0	1	2	201	0.387	103	0.012
	202	0.005	202	0.004	196	0.005	197	0.004	797	0.004	2	3	201	0.387	157	0.018
	31	0.001	31	0.001	31	0.001	31	0.001	124	0.001	2	4	201	0.387	221	0.026
	390	0.01	862	0.017	831	0.02	831	0.017	2914	0.016	2	5	201	0.387	275	0.032
	0	0	0	0	228	0.006	0	0	228	0.001	1	3	201	0.387	313	0.037
	127	0.003	375	0.008	110	0.003	138	0.003	750	0.004	2	6	201	0.387	327	0.038
	34	0.001	55	0.001	55	0.001	219	0.004	363	0.002	2	7	201	0.387	385	0.045
	0	0	0	0	128	0.003	0	0	128	0.001	1	4	201	0.387	441	0.052
	229	0.006	323	0.006	152	0.004	173	0.003	877	0.005	2	8	201	0.387	457	0.054
	3806	0.101	10279	0.207	6162	0.152	8212	0.166	28459	0.16	1	5	201	0.387	551	0.065
	0	0	0	0	0	0	53	0.001	53	0	1	6	201	0.387	655	0.077
	2067	0.055	2223	0.045	2016	0.05	2709	0.055	9015	0.051	2	10	207	0.398	671	0.079
	507	0.013	719	0.014	702	0.017	749	0.015	2677	0.015	1	7	201	0.387	771	0.091
	107	0.003	107	0.002	107	0.003	107	0.002	428	0.002	2	11	229	0.44	830	0.098
	890	0.024	1471	0.03	1044	0.026	1246	0.025	4651	0.026	1	8	201	0.387	914	0.108
	217	0.006	217	0.004	223	0.005	223	0.004	880	0.005	2	12	251	0.483	1033	0.122
	0	0	0	0	121	0.003	162	0.003	283	0.002	1	9	201	0.387	1099	0.129
	259	0.007	580	0.012	254	0.006	254	0.005	1347	0.008	2	13	276	0.531	1289	0.152
	2472	0.065	7099	0.143	5072	0.125	5148	0.104	19791	0.111	1	10	207	0.398	1342	0.158
	569	0.015	304	0.006	313	0.008	313	0.006	1499	0.008	2	14	298	0.573	1604	0.189
	0	0	2245	0.045	0	0	2052	0.041	4297	0.024	1	11	229	0.44	1660	0.195
	585	0.015	585	0.012	1122	0.028	663	0.013	2955	0.017	2	15	320	0.615	1988	0.234
	330	0.009	785	0.016	425	0.01	710	0.014	2250	0.013	1	12	251	0.483	2066	0.243
	803	0.021	777	0.016	407	0.01	400	0.008	2387	0.013	2	16	342	0.658	2448	0.288
	0	0	870	0.017	56	0.001	879	0.018	1805	0.01	1	13	276	0.531	2577	0.303
	916	0.024	916	0.018	433	0.011	442	0.009	2707	0.015	2	17	364	0.7	2991	0.352
	634	0.017	1950	0.039	53	0.001	2536	0.051	5173	0.029	1	14	298	0.573	3209	0.378
	393	0.01	393	0.008	331	0.008	331	0.007	1448	0.008	2	18	386	0.742	3625	0.426
	3190	0.084	2122	0.043	3717	0.091	1832	0.037	10861	0.061	1	15	320	0.615	3976	0.468
	336	0.009	336	0.007	48	0.001	48	0.001	768	0.004	2	19	408	0.785	4359	0.513
	2157	0.057	2097	0.042	1207	0.03	3592	0.072	9053	0.051	1	16	342	0.658	4895	0.576
	486	0.013	486	0.01	499	0.012	499	0.01	1970	0.011	2	20	433	0.833	5199	0.612
	7597	0.201	3112	0.063	4901	0.121	5540	0.112	21150	0.119	1	17	370	0.712	5981	0.704
	1226	0.032	1226	0.025	142	0.003	142	0.003	2736	0.015	2	21	455	0.875	6155	0.724
	1520	0.04	1520	0.031	2160	0.053	1720	0.035	6920	0.039	2	22	477	0.917	7232	0.851
	2239	0.059	502	0.01	2328	0.057	66	0.001	5135	0.029	1	18	382	0.735	7250	0.853
	336	0.009	336	0.007	2124	0.052	2124	0.043	4920	0.028	2	23	498	0.958	8440	0.993
	675	0.018	2413	0.049	415	0.01	2817	0.057	6320	0.036	2	24	520	1	8500	1
Total:	37792	1	49719	1	40668	1	49556	1	177735	1						

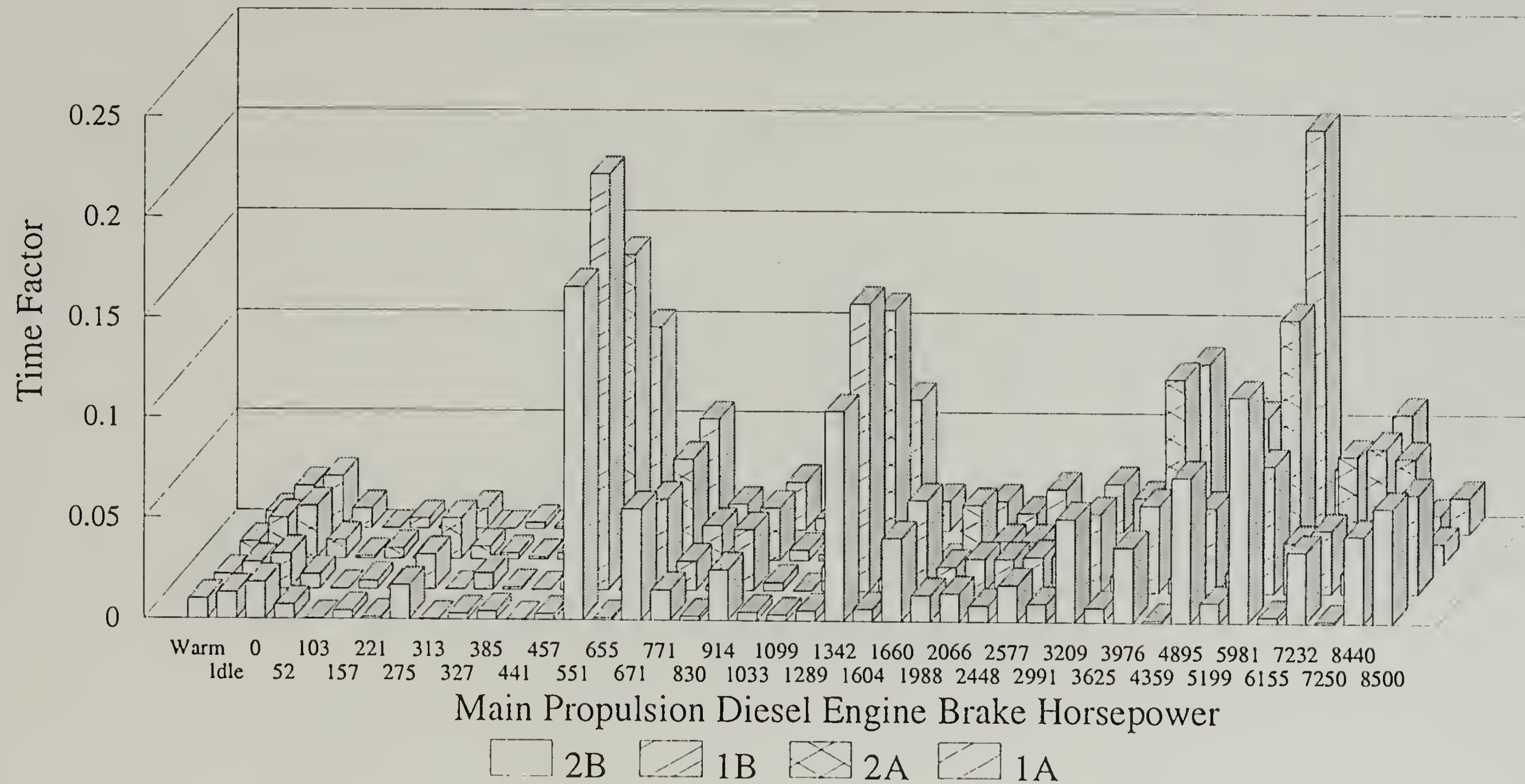

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Figure B-1: LSD 43 Individual MPE Operating Profiles

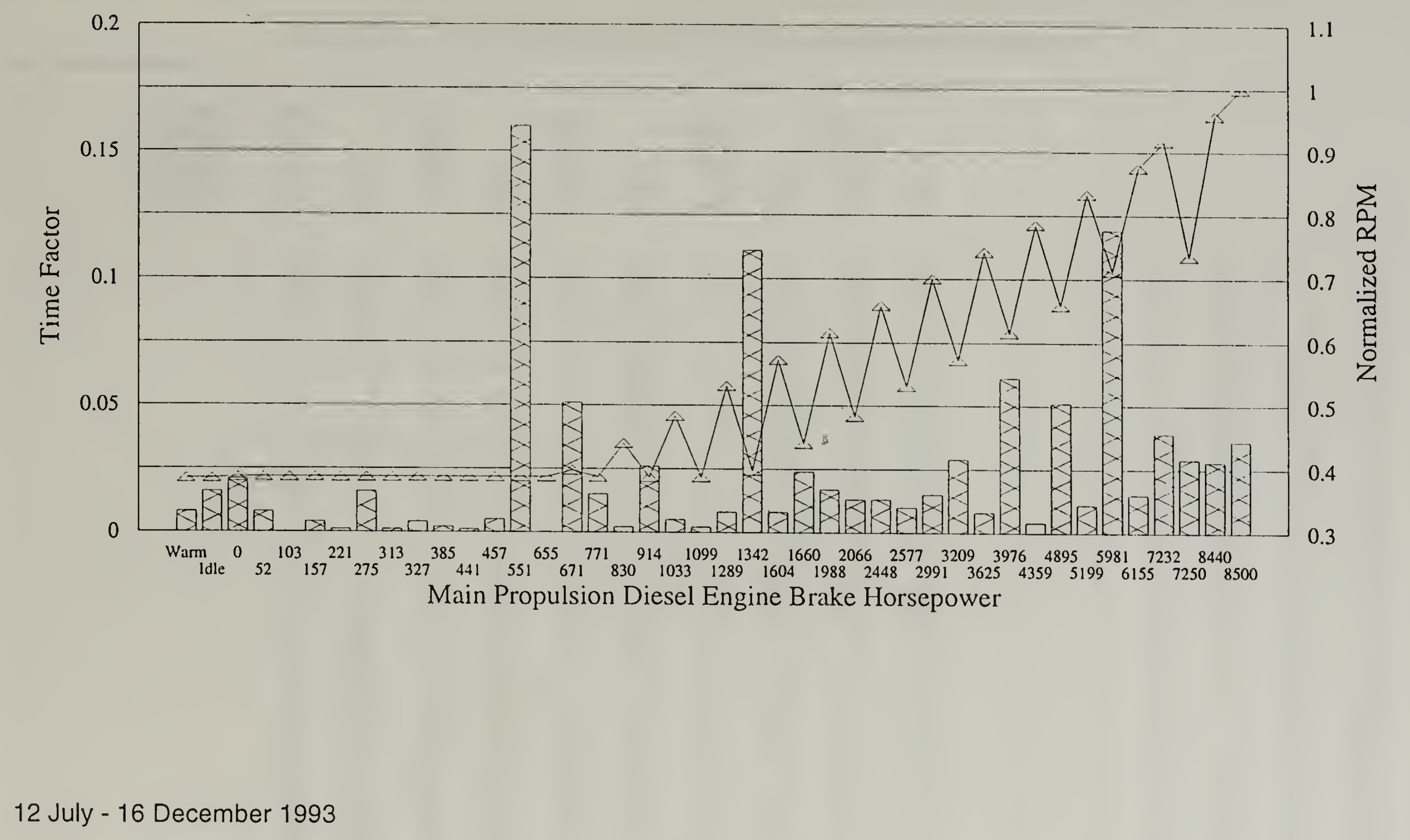

Figure B-2: LSD 43 Composite Operating Profile

Table B-3: *USS GUNSTON HALL* (LSD 44) MPE Data Summary

MPE Time Factor Calculations	1A	1A_n	1B	1B-n	2A	2A_n	2B	2B_n	Total	Total_n						
Data Points:	695		704		689		728		2816							
Total Time:	32419		33794		31159		35680		133052							
Time Secured:	13887		12888		13301		14423		54499							
Time Running:	18532	1	20906	1	17858	1	21257	1	78553	1						
Time Warming Up:	286	0.015	353	0.017	309	0.017	358	0.017	1306	0.017						
Time at Idle:	396	0.021	380	0.018	563	0.032	386	0.018	1725	0.022						
Time at Power:	17850	0.963	20173	0.965	16986	0.951	20513	0.965	75522	0.961						
											Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
	286	0.015	353	0.017	309	0.017	358	0.017	1306	0.017			200	0.385	Warm	0
	396	0.021	380	0.018	563	0.032	386	0.018	1725	0.022			200	0.385	Idle	0
	1781	0.096	1887	0.09	1884	0.105	1817	0.085	7369	0.094	All Stop	0	201	0.387	0	0
	172	0.009	172	0.008	166	0.009	166	0.008	676	0.009	2	2	201	0.387	52	0.006
	0	0	0	0	5	0	0	0	5	0	1	2	201	0.387	103	0.012
	72	0.004	72	0.003	72	0.004	72	0.003	288	0.004	2	3	201	0.387	157	0.018
	166	0.009	166	0.008	168	0.009	168	0.008	668	0.009	2	4	201	0.387	221	0.026
	761	0.041	718	0.034	717	0.04	714	0.034	2910	0.037	2	5	201	0.387	275	0.032
	0	0	0	0	38	0.002	0	0	38	0	1	3	201	0.387	313	0.037
	0	0	95	0.005	95	0.005	88	0.004	278	0.004	2	6	201	0.387	327	0.038
	316	0.017	139	0.007	139	0.008	139	0.007	733	0.009	2	7	201	0.387	385	0.045
	47	0.003	149	0.007	24	0.001	172	0.008	392	0.005	1	4	201	0.387	441	0.052
	57	0.003	57	0.003	57	0.003	57	0.003	228	0.003	2	8	201	0.387	457	0.054
	944	0.051	1710	0.082	867	0.049	1617	0.076	5138	0.065	1	5	201	0.387	551	0.065
	0	0	86	0	0	0	0	0	86	0.001	1	6	201	0.387	655	0.077
	1565	0.084	1527	0.073	1307	0.073	1387	0.065	5786	0.074	2	10	207	0.398	671	0.079
	87	0.005	462	0.022	102	0.006	285	0.013	936	0.012	1	7	201	0.387	771	0.091
	0	0	0	0	0	0	0	0	0	0	2	11	229	0.44	830	0.098
	5	0	74	0.004	0	0	79	0.004	158	0.002	1	8	201	0.387	914	0.108
	216	0.012	216	0.01	209	0.012	209	0.01	850	0.011	2	12	251	0.483	1033	0.122
	0	0	0	0	0	0	0	0	0	0	1	9	201	0.387	1099	0.129
	425	0.023	425	0.02	400	0.022	400	0.019	1650	0.021	2	13	276	0.531	1289	0.152
	1509	0.081	1256	0.06	2033	0.114	1052	0.049	5850	0.074	1	10	207	0.398	1342	0.158
	96	0.005	96	0.005	96	0.005	96	0.005	384	0.005	2	14	298	0.573	1604	0.189
	59	0.003	0	0	34	0.002	25	0.001	118	0.002	1	11	229	0.44	1660	0.195
	801	0.043	801	0.038	772	0.043	782	0.037	3156	0.04	2	15	320	0.615	1988	0.234
	159	0.009	113	0.005	169	0.009	4	0	445	0.006	1	12	251	0.483	2066	0.243
	575	0.031	575	0.028	502	0.028	502	0.024	2154	0.027	2	16	342	0.658	2448	0.288
	110	0.006	13	0.001	4	0	118	0.006	245	0.003	1	13	276	0.531	2577	0.303
	60	0.003	60	0.003	362	0.02	362	0.017	844	0.011	2	17	364	0.7	2991	0.352
	439	0.024	0	0	13	0.001	426	0.02	878	0.011	1	14	298	0.573	3209	0.378
	489	0.026	489	0.023	489	0.027	489	0.023	1956	0.025	2	18	386	0.742	3625	0.426
	1443	0.078	1090	0.052	1176	0.066	1378	0.065	5087	0.065	1	15	320	0.615	3976	0.468
	1512	0.082	1512	0.072	1512	0.085	1512	0.071	6048	0.077	2	19	408	0.785	4359	0.513
	291	0.016	190	0.009	261	0.015	295	0.014	1037	0.013	1	16	342	0.658	4895	0.576
	2409	0.13	2409	0.115	2406	0.135	2406	0.113	9630	0.123	2	20	433	0.833	5199	0.612
	199	0.011	2597	0.124	101	0.006	2393	0.113	5290	0.067	1	17	370	0.712	5981	0.704
	104	0.006	104	0.005	104	0.006	104	0.005	416	0.005	2	21	455	0.875	6155	0.724
	660	0.036	660	0.032	660	0.037	660	0.031	2640	0.034	2	22	477	0.917	7232	0.851
	286	0.015	216	0.01	5	0	502	0.024	1009	0.013	1	18	382	0.735	7250	0.853
	37	0.002	37	0.002	37	0.002	37	0.002	148	0.002	2	23	498	0.958	8440	0.993
	0	0	0	0	0	0	0	0	0	0	2	24	520	1	8500	1
Total:	18534	1	20906	1	17858	1	21257	1	78555	1						

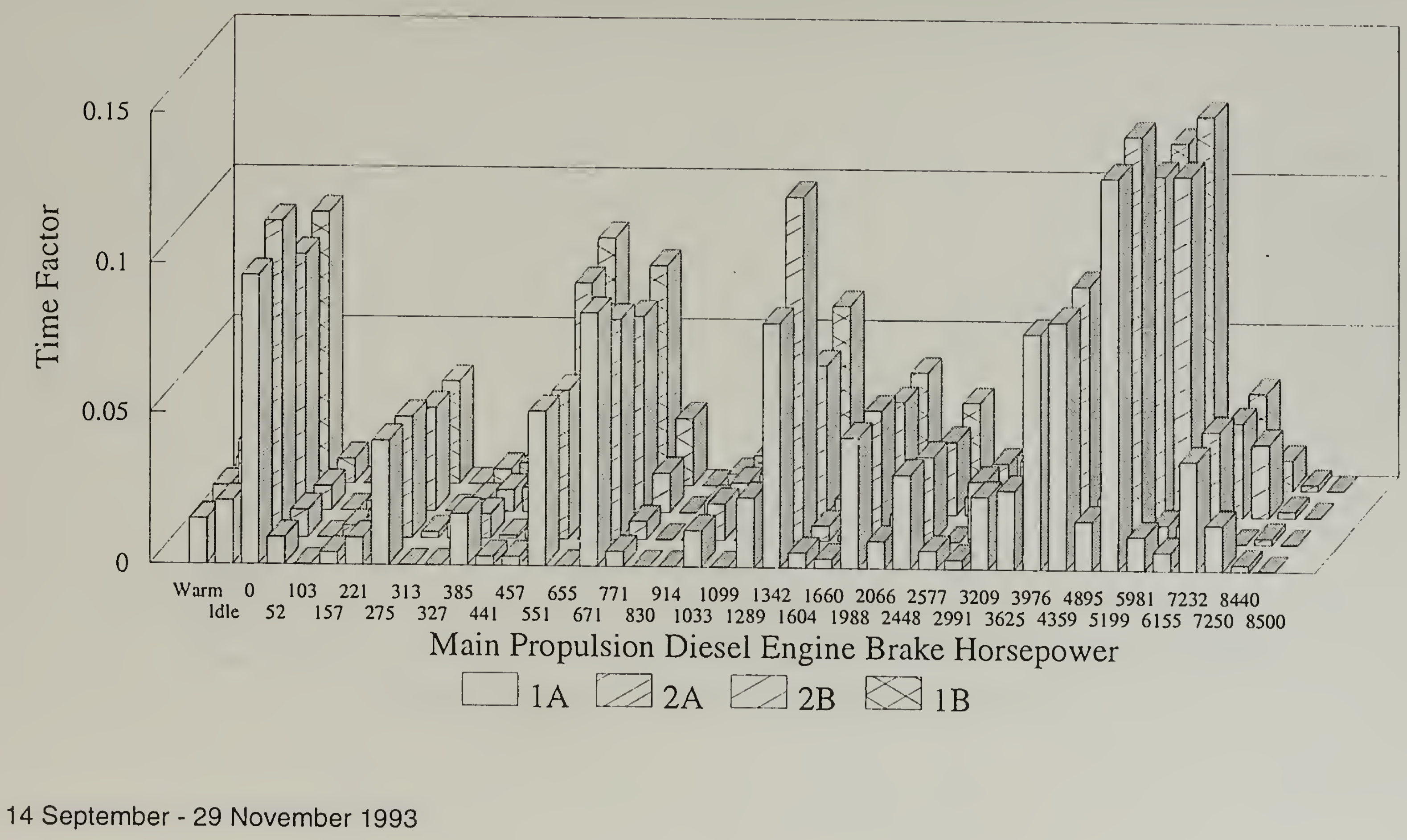

Figure B-3: LSD 44 Individual MPE Operating Profiles

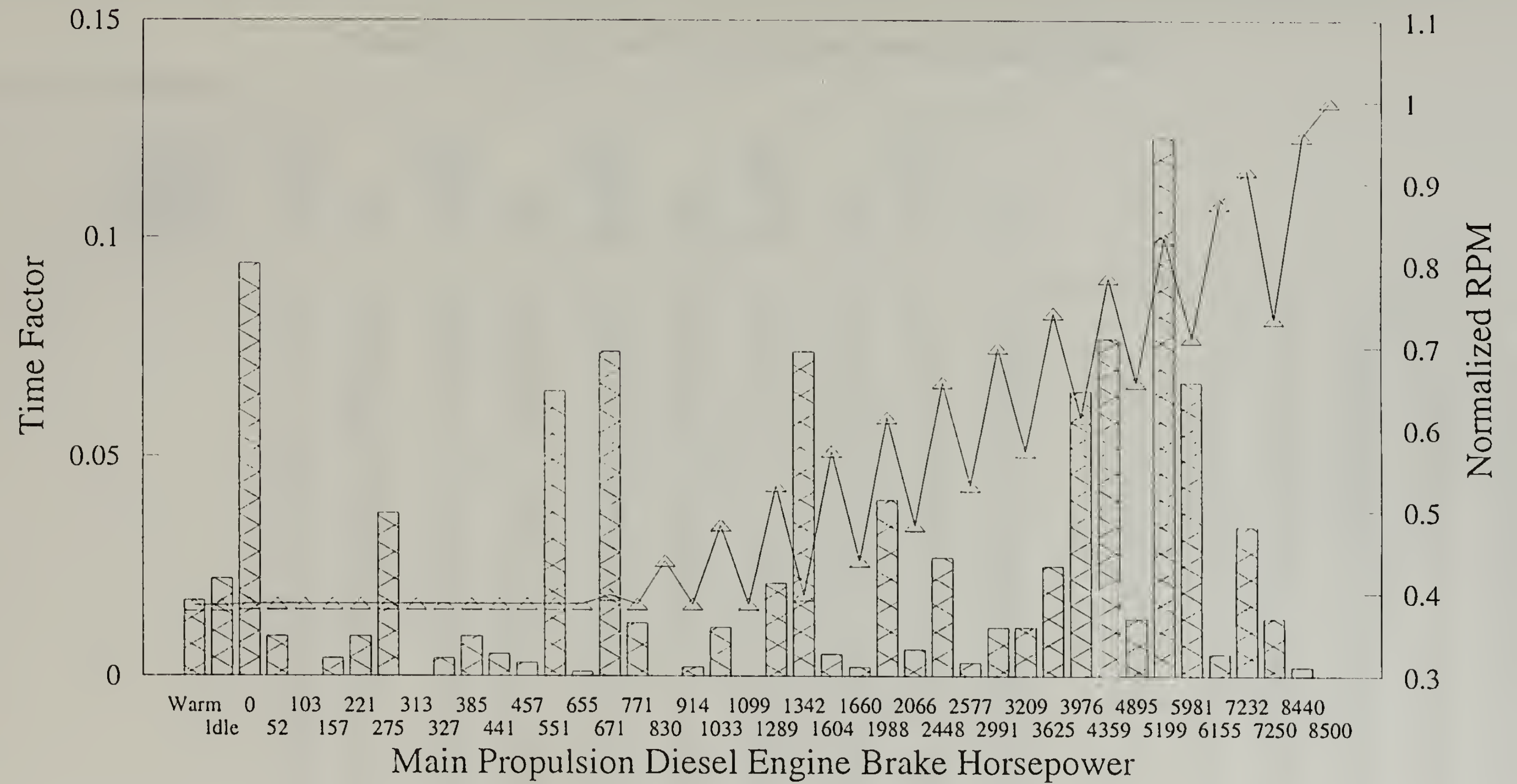

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Figure B-4: LSD 44 Composite Operating Profile

B.3: *USS TORTUGA* (LSD 46)

Table B-2: *USS TORTUGA* (LSD 46) MPE Data Summary

MPE Time Factor Calculations	IA	1A_n	1B	1B-n	2A	2A_n	2B	2B_n	Total	Total_n						
Data Points:	1056		1026		1033		1152		4267							
• Total Time:	43329		34985		39539		41992		159845							
Time Secured:	20732		18945		18502		18693		76872							
Time Running:	22597	1	16040	1	21037	1	23299	1	82973	1						
Time Warming Up:	521	0.023	501	0.031	422	0.02	448	0.019	1892	0.023						
Time at Idle:	531	0.023	551	0.034	662	0.031	613	0.026	2357	0.028						
Time at Power:	21545	0.953	14988	0.934	19953	0.948	22238	0.954	78724	0.949						
											Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
	521	0.023	501	0.031	422	0.02	448	0.019	1892	0.023			200	0.385	Warm	0
	531	0.023	551	0.034	662	0.031	613	0.026	2357	0.028			200	0.385	Idle	0
	1127	0.05	1064	0.066	1137	0.054	1209	0.052	4537	0.055	All Stop	0	201	0.387	0	0
	366	0.016	366	0.023	359	0.017	424	0.018	1515	0.018	2	2	201	0.387	52	0.006
	19	0.001	36	0.002	12	0.001	55	0.002	122	0.001	1	2	201	0.387	103	0.012
	160	0.007	159	0.01	179	0.009	226	0.01	724	0.009	2	3	201	0.387	157	0.018
	71	0.003	71	0.004	53	0.003	69	0.003	264	0.003	2	4	201	0.387	221	0.026
	968	0.043	967	0.06	762	0.036	883	0.038	3580	0.043	2	5	201	0.387	275	0.032
	22	0.001	11	0.001	81	0.004	3	0	117	0.001	1	3	201	0.387	313	0.037
	10	0	6	0	10	0	6	0	32	0	2	6	201	0.387	327	0.038
	152	0.007	152	0.009	103	0.005	103	0.004	510	0.006	2	7	201	0.387	385	0.045
	11	0	0	0	8	0	3	0	22	0	1	4	201	0.387	441	0.052
	60	0.003	60	0.004	58	0.003	66	0.003	244	0.003	2	8	201	0.387	457	0.054
	41	0.002	41	0.003	53	0.003	53	0.002	188	0.002	2	9	201	0.387	549	0.065
	1325	0.059	774	0.048	793	0.038	1421	0.061	4313	0.052	1	5	201	0.387	551	0.065
	0	0	357	0	75	0.004	282	0.012	714	0.009	1	6	201	0.387	655	0.077
	1164	0.052	1039	0.065	1038	0.049	1024	0.044	4265	0.051	2	10	207	0.398	671	0.079
	1135	0.05	63	0.004	711	0.034	1303	0.056	3212	0.039	1	7	201	0.387	771	0.091
	51	0.002	51	0.003	51	0.002	51	0.002	204	0.002	2	11	229	0.44	830	0.098
	170	0.008	384	0.024	327	0.016	227	0.01	1108	0.013	1	8	201	0.387	914	0.108
	625	0.028	555	0.035	589	0.028	611	0.026	2380	0.029	2	12	251	0.483	1033	0.122
	0	0	46	0.003	34	0.002	362	0.016	442	0.005	1	9	201	0.387	1099	0.129
	253	0.011	253	0.016	201	0.01	305	0.013	1012	0.012	2	13	276	0.531	1289	0.152
	2088	0.092	1222	0.076	1593	0.076	1744	0.075	6647	0.08	1	10	207	0.398	1342	0.158
	298	0.013	298	0.019	240	0.011	316	0.014	1152	0.014	2	14	298	0.573	1604	0.189
	0	0	21	0.001	0	0	23	0.001	44	0.001	1	11	229	0.44	1660	0.195
	1073	0.047	1170	0.073	951	0.045	1437	0.062	4631	0.056	2	15	320	0.615	1988	0.234
	1031	0.046	548	0.034	1110	0.053	429	0.018	3118	0.038	1	12	251	0.483	2066	0.243
	280	0.012	280	0.017	389	0.018	443	0.019	1392	0.017	2	16	342	0.658	2448	0.288
	84	0.004	247	0.015	237	0.011	94	0.004	662	0.008	1	13	276	0.531	2577	0.303
	590	0.026	581	0.036	634	0.03	661	0.028	2466	0.03	2	17	364	0.7	2991	0.352
	43	0.002	263	0.016	0	0	263	0.011	569	0.007	1	14	298	0.573	3209	0.378
	271	0.012	271	0.017	204	0.01	354	0.015	1100	0.013	2	18	386	0.742	3625	0.426
	1071	0.047	392	0.024	598	0.028	957	0.041	3018	0.036	1	15	320	0.615	3976	0.468
	88	0.004	88	0.005	125	0.006	125	0.005	426	0.005	2	19	408	0.785	4359	0.513
	782	0.035	1134	0.071	938	0.045	538	0.023	3392	0.041	1	16	342	0.658	4895	0.576
	603	0.027	603	0.038	608	0.029	714	0.031	2528	0.03	2	20	433	0.833	5199	0.612
	3400	0.15	330	0.021	1354	0.064	577	0.025	5661	0.068	1	17	370	0.712	5981	0.704
	86	0.004	86	0.005	1158	0.055	1158	0.05	2488	0.03	2	21	455	0.875	6155	0.724
	184	0.008	184	0.011	412	0.02	412	0.018	1192	0.014	2	22	477	0.917	7232	0.851
	2	0	0	0	0	0	0	0	2	0	1	18	382	0.735	7250	0.853
	171	0.008	171	0.011	171	0.008	171	0.007	684	0.008	2	23	498	0.958	8440	0.993
	1670	0.074	644	0.04	2597	0.123	3146	0.135	8057	0.097	2	24	520	1	8500	1
Total:	22597	1	16040	1	21037	1	23309	1	82983	1						

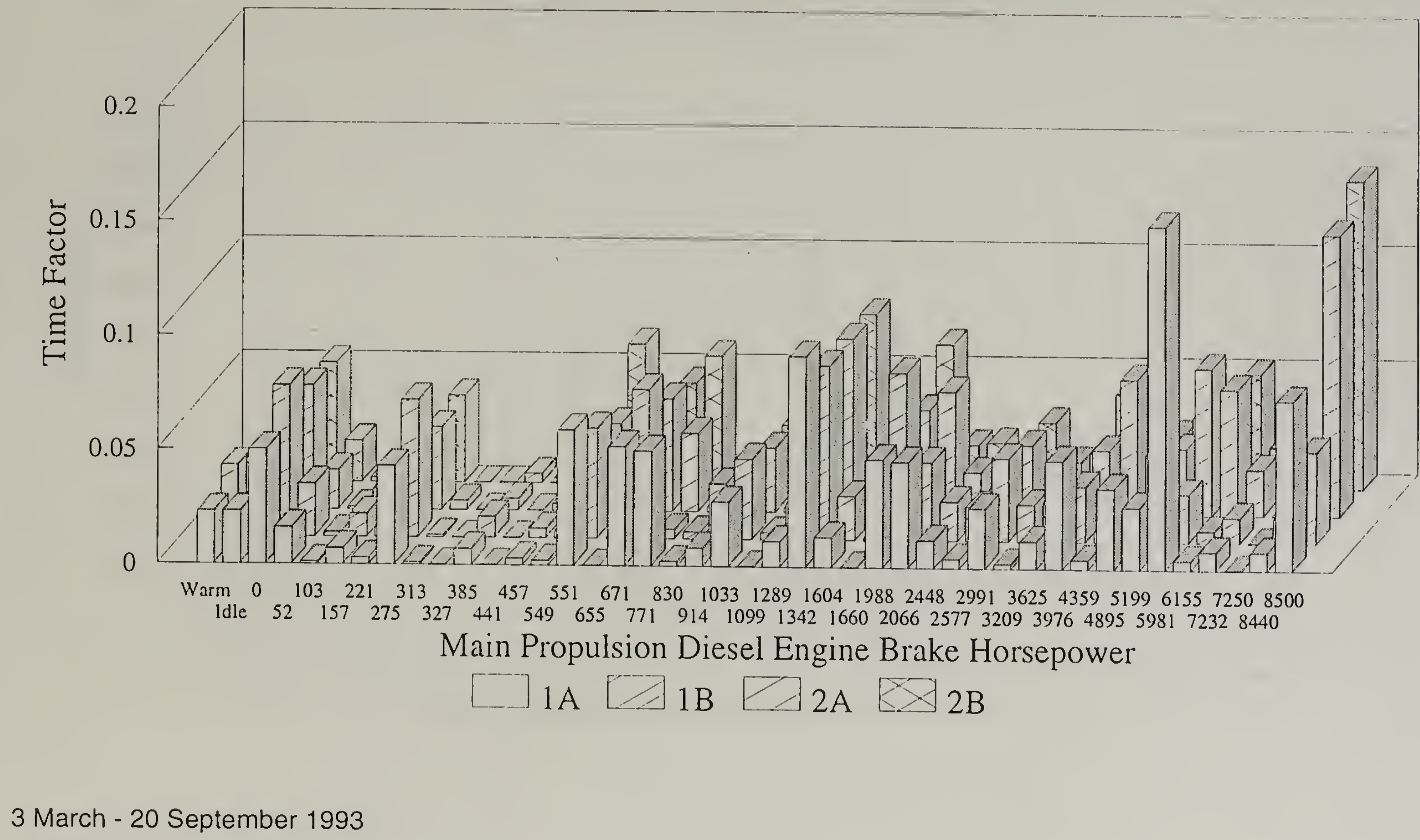

Figure B-5: LSD 46 Individual MPE Operating Profiles

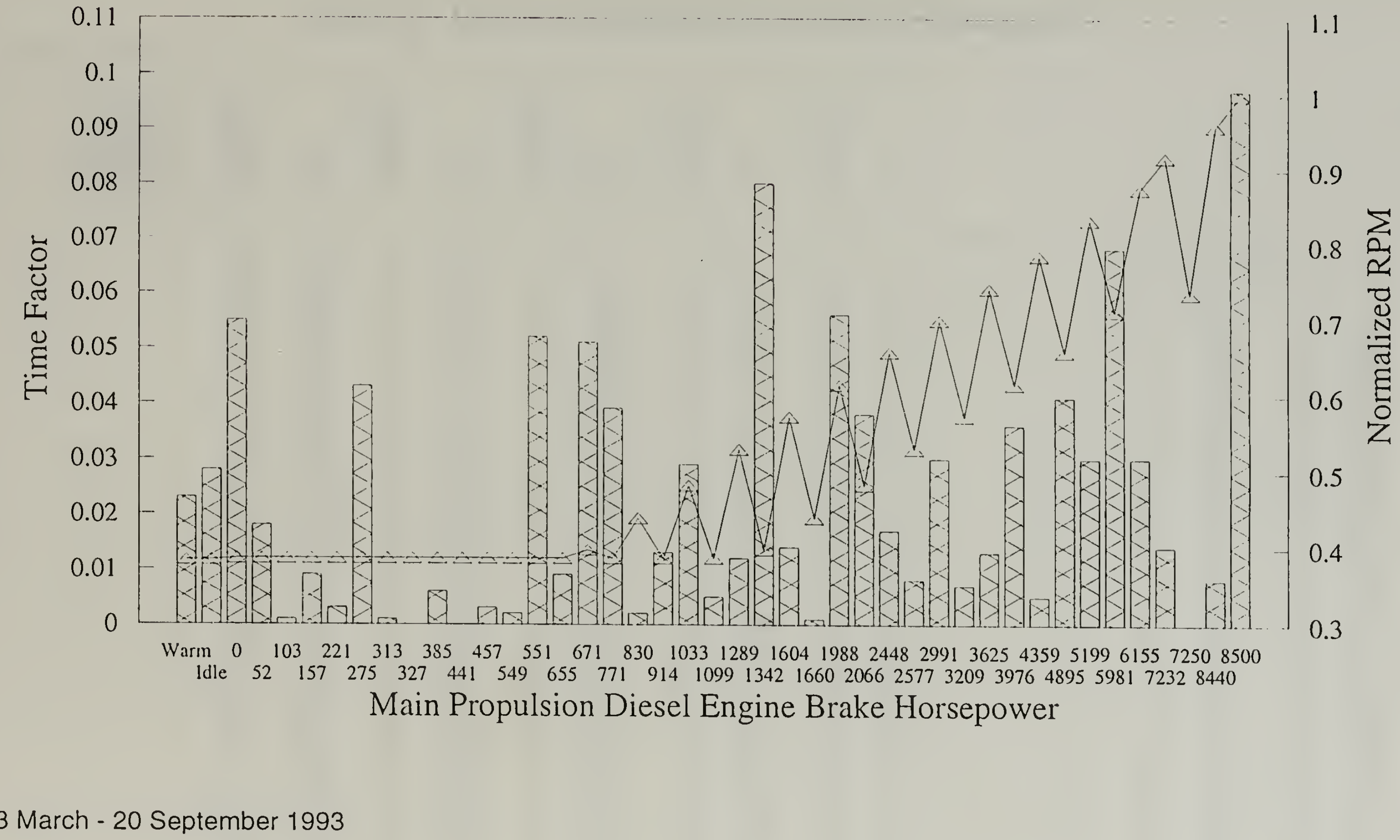

Figure B-6: LSD 46 Composite Operating Profile

B.4: *USS RUSHMORE* (LSD 47)

Table B-5: *USS RUSHMORE* (LSD 47) MPE Data Summary

MPE Time Factor Calculations	1A	1A_n	1B	1B-n	2A	2A_n	2B	2B_n	Total	Total_n						
Data Points:	764		791		730		728		3013							
Total Time:	41529		34868		40651		28469		145517							
Time Secured:	12201		12768		11610		14446		51025							
Time Running:	29328	1	22100	1	29041	1	14023	1	94492	1						
Time Warming Up:	441	0.015	380	0.017	368	0.013	382	0.027	1571	0.017						
Time at Idle:	237	0.008	353	0.016	272	0.009	293	0.021	1155	0.012						
Time at Power:	28650	0.977	21367	0.967	28401	0.978	13348	0.952	91766	0.971						
											Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
	441	0.015	380	0.017	368	0.013	382	0.027	1571	0.017			200	0.385	Warm	0
	237	0.008	353	0.016	272	0.009	293	0.021	1155	0.012			200	0.385	Idle	0
	1027	0.035	994	0.045	1549	0.053	1441	0.103	5011	0.053	All Stop	0	201	0.387	0	0
	694	0.024	694	0.031	127	0.004	127	0.009	1642	0.017	2	2	201	0.387	52	0.006
	53	0.002	0	0	53	0.002	0	0	106	0.001	1	2	201	0.387	103	0.012
	432	0.015	432	0.02	329	0.011	329	0.023	1522	0.016	2	3	201	0.387	157	0.018
	68	0.002	68	0.003	47	0.002	47	0.003	230	0.002	2	4	201	0.387	221	0.026
	1572	0.054	1586	0.072	790	0.027	772	0.055	4720	0.05	2	5	201	0.387	275	0.032
	28	0.001	0	0	28	0.001	0	0	56	0.001	1	3	201	0.387	313	0.037
	71	0.002	71	0.003	65	0.002	65	0.005	272	0.003	2	6	201	0.387	327	0.038
	191	0.007	191	0.009	171	0.006	158	0.011	711	0.008	2	7	201	0.387	385	0.045
	163	0.006	75	0.003	40	0.001	200	0.014	478	0.005	1	4	201	0.387	441	0.052
	127	0.004	127	0.006	78	0.003	78	0.006	410	0.004	2	8	201	0.387	457	0.054
	305	0.01	305	0.014	172	0.006	172	0.012	954	0.01	2	9	201	0.387	549	0.065
	1501	0.051	1991	0.09	1537	0.053	1238	0.088	6267	0.066	1	5	201	0.387	551	0.065
	251	0.009	501	0.023	173	0.006	335	0.024	1260	0.013	1	6	201	0.387	655	0.077
	1517	0.052	1503	0.068	1030	0.035	1055	0.075	5105	0.054	2	10	207	0.398	671	0.079
	47	0.002	368	0.017	217	0.007	110	0.008	742	0.008	1	7	201	0.387	771	0.091
	18	0.001	18	0.001	20	0.001	20	0.001	76	0.001	2	11	229	0.44	830	0.098
	28	0.001	156	0.007	28	0.001	156	0.011	368	0.004	1	8	201	0.387	914	0.108
	218	0.007	218	0.01	240	0.008	240	0.017	916	0.01	2	12	251	0.483	1033	0.122
	0	0	107	0.005	4	0	103	0.007	214	0.002	1	9	201	0.387	1099	0.129
	128	0.004	128	0.006	81	0.003	81	0.006	418	0.004	2	13	276	0.531	1289	0.152
	748	0.026	1104	0.05	736	0.025	1341	0.096	3929	0.042	1	10	207	0.398	1342	0.158
	650	0.022	671	0.03	25	0.001	4	0	1350	0.014	2	14	298	0.573	1604	0.189
	142	0.005	1034	0.047	358	0.012	582	0.042	2116	0.022	1	11	229	0.44	1660	0.195
	816	0.028	808	0.037	529	0.018	521	0.037	2674	0.028	2	15	320	0.615	1988	0.234
	2202	0.075	995	0.045	2712	0.093	566	0.04	6475	0.069	1	12	251	0.483	2066	0.243
	112	0.004	112	0.005	133	0.005	149	0.011	506	0.005	2	16	342	0.658	2448	0.288
	3363	0.115	795	0.036	3947	0.136	166	0.012	8271	0.088	1	13	276	0.531	2577	0.303
	105	0.004	105	0.005	87	0.003	87	0.006	384	0.004	2	17	364	0.7	2991	0.352
	1428	0.049	1330	0.06	2645	0.091	78	0.006	5481	0.058	1	14	298	0.573	3209	0.378
	74	0.003	74	0.003	74	0.003	74	0.005	296	0.003	2	18	386	0.742	3625	0.426
	1872	0.064	987	0.045	1888	0.065	969	0.069	5716	0.06	1	15	320	0.615	3976	0.468
	14	0	14	0.001	0	0	0	0	28	0	2	19	408	0.785	4359	0.513
	1656	0.056	419	0.019	1593	0.055	460	0.033	4128	0.044	1	16	342	0.658	4895	0.576
	128	0.004	128	0.006	128	0.004	128	0.009	512	0.005	2	20	433	0.833	5199	0.612
	4850	0.165	1102	0.05	6481	0.223	1042	0.074	13475	0.143	1	17	370	0.712	5981	0.704
	383	0.013	383	0.017	21	0.001	21	0.001	808	0.009	2	21	455	0.875	6155	0.724
	291	0.01	291	0.013	95	0.003	95	0.007	772	0.008	2	22	477	0.917	7232	0.851
	1	0	97	0.004	1	0	97	0.007	196	0.002	1	18	382	0.735	7250	0.853
	1157	0.039	1157	0.052	0	0	0	0	2314	0.024	2	23	498	0.958	8440	0.993
	219	0.007	228	0.01	169	0.006	241	0.017	857	0.009	2	24	520	1	8500	1
Total:	29328	1	22100	1	29041	1	14023	1	94492	1						

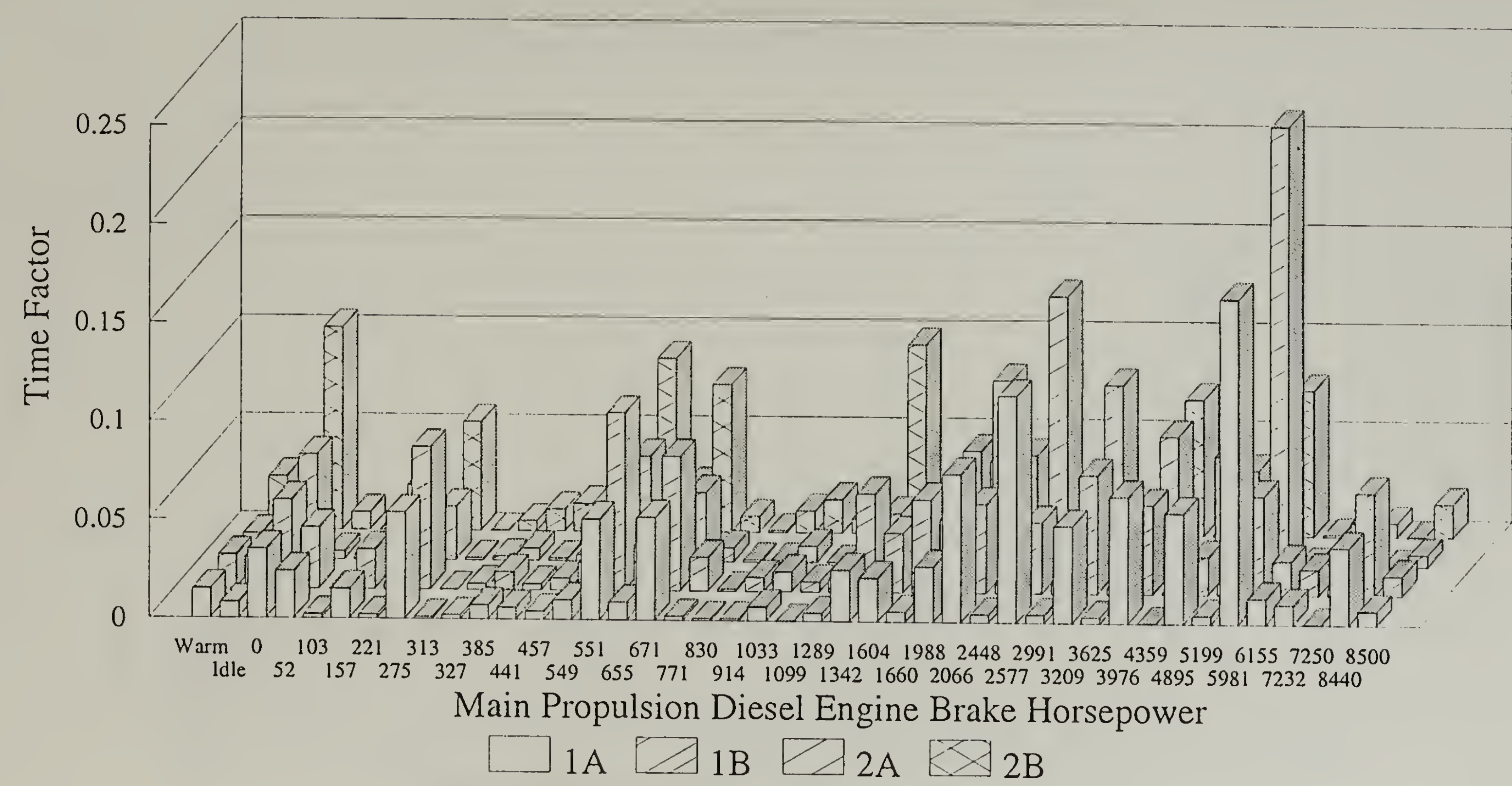

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Figure B-7: LSD 47 Individual MPE Operating Profiles

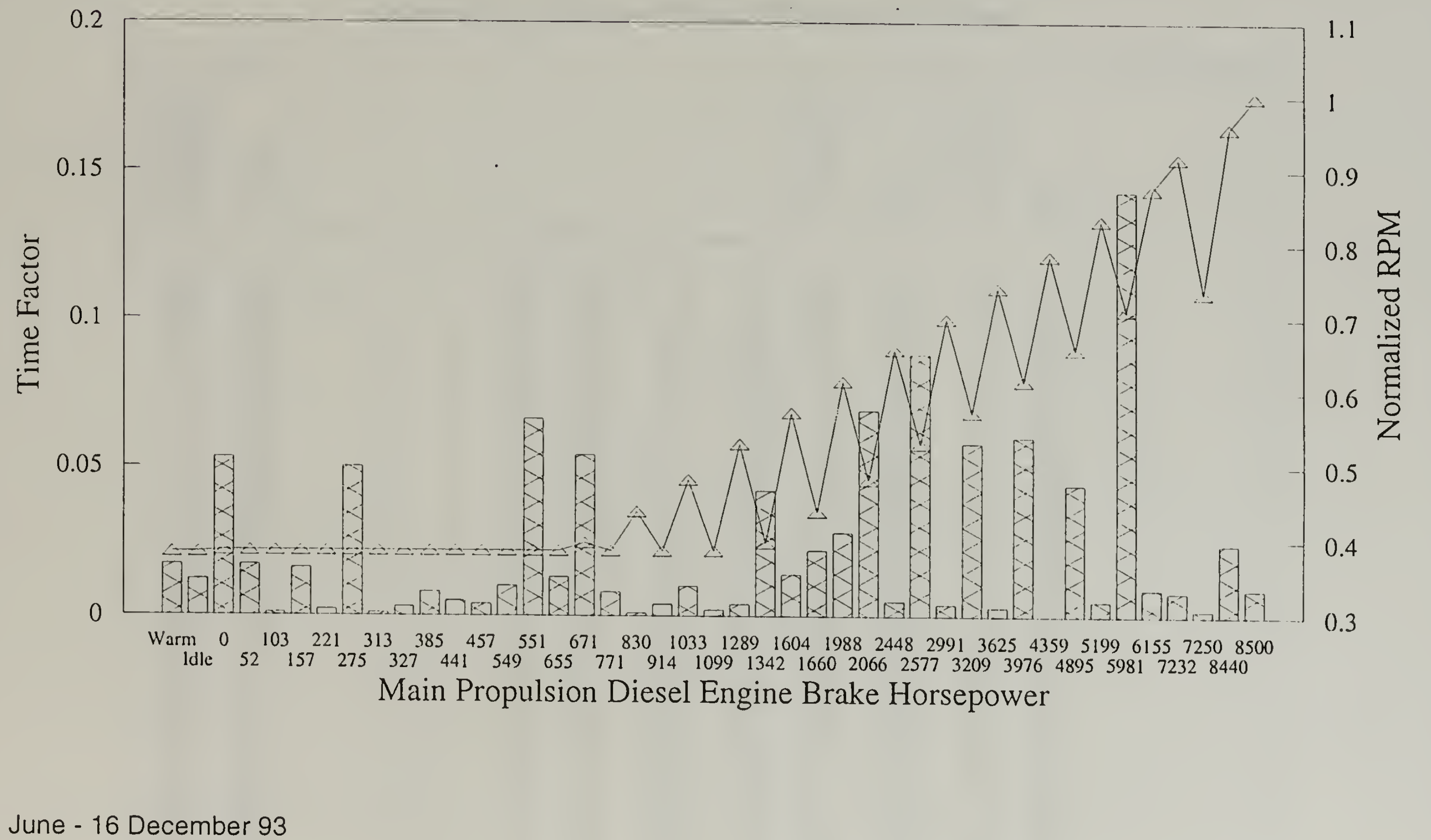

Figure B-8: LSD 47 Composite Operating Profile

B.5: Ship Visit Summary

Table B-6: MPE Time Factor Summary by Coast

Total	Total_n							East	East_n	West	West_n	MPE Time Factor by Coast
15107								7083		8024		
690738								292897		397841		
256985								131371		125614		
433753	1							161526	1	272227	1	
6227	0.014							3198	0.02	3029	0.011	
8123	0.019							4082	0.025	4041	0.015	
419403	0.967							154246	0.955	265157	0.974	
		Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n					
6227	0.014			200	0.385	Warm	0	3198	0.02	3029	0.011	
8123	0.019			200	0.385	Idle	0	4082	0.025	4041	0.015	
20682	0.048	All Stop	0	201	0.387	0	0	11906	0.074	8776	0.032	
5270	0.012	2	2	201	0.387	52	0.006	2191	0.014	3079	0.011	
303	0.001	1	2	201	0.387	103	0.012	127	0.001	176	0.001	
3331	0.008	2	3	201	0.387	157	0.018	1012	0.006	2319	0.009	
1286	0.003	2	4	201	0.387	221	0.026	932	0.006	354	0.001	
14124	0.033	2	5	201	0.387	275	0.032	6490	0.04	7634	0.028	
439	0.001	1	3	201	0.387	313	0.037	155	0.001	284	0.001	
1332	0.003	2	6	201	0.387	327	0.038	310	0.002	1022	0.004	
2317	0.005	2	7	201	0.387	385	0.045	1243	0.008	1074	0.004	
1020	0.002	1	4	201	0.387	441	0.052	414	0.003	606	0.002	
1759	0.004	2	8	201	0.387	457	0.054	472	0.003	1287	0.005	
1142	0.003	2	9	201	0.387	549	0.065	188	0.001	954	0.004	
44177	0.102	1	5	201	0.387	551	0.065	9451	0.059	34726	0.128	
2113	0.005	1	6	201	0.387	655	0.077	800	0.005	1313	0.005	
24171	0.056	2	10	207	0.398	671	0.079	10051	0.062	14120	0.052	
7567	0.017	1	7	201	0.387	771	0.091	4148	0.026	3419	0.013	
708	0.002	2	11	229	0.44	830	0.098	204	0.001	504	0.002	
6285	0.014	1	8	201	0.387	914	0.108	1266	0.008	5019	0.018	
5026	0.012	2	12	251	0.483	1033	0.122	3230	0.02	1796	0.007	
939	0.002	1	9	201	0.387	1099	0.129	442	0.003	497	0.002	
4427	0.01	2	13	276	0.531	1289	0.152	2662	0.016	1765	0.006	
36217	0.083	1	10	207	0.398	1342	0.158	12497	0.077	23720	0.087	
4385	0.01	2	14	298	0.573	1604	0.189	1536	0.01	2849	0.01	
6575	0.015	1	11	229	0.44	1660	0.195	162	0.001	6413	0.024	
13416	0.031	2	15	320	0.615	1988	0.234	7787	0.048	5629	0.021	
12288	0.028	1	12	251	0.483	2066	0.243	3563	0.022	8725	0.032	
6439	0.015	2	16	342	0.658	2448	0.288	3546	0.022	2893	0.011	
10983	0.025	1	13	276	0.531	2577	0.303	907	0.006	10076	0.037	
6401	0.015	2	17	364	0.7	2991	0.352	3310	0.02	3091	0.011	
12101	0.028	1	14	298	0.573	3209	0.378	1447	0.009	10654	0.039	
4800	0.011	2	18	386	0.742	3625	0.426	3056	0.019	1744	0.006	
24682	0.057	1	15	320	0.615	3976	0.468	8105	0.05	16577	0.061	
7270	0.017	2	19	408	0.785	4359	0.513	6474	0.04	796	0.003	
17610	0.041	1	16	342	0.658	4895	0.576	4429	0.027	13181	0.048	
14640	0.034	2	20	433	0.833	5199	0.612	12158	0.075	2482	0.009	
45576	0.105	1	17	370	0.712	5981	0.704	10951	0.068	34625	0.127	
6448	0.015	2	21	455	0.875	6155	0.724	2904	0.018	3544	0.013	
11524	0.027	2	22	477	0.917	7232	0.851	3832	0.024	7692	0.028	
6342	0.015	1	18	382	0.735	7250	0.853	1011	0.006	5331	0.02	
8066	0.019	2	23	498	0.958	8440	0.993	832	0.005	7234	0.027	
15234	0.035	2	24	520	1	8500	1	8057	0.05	7177	0.026	
433765	1							161538	1	272227	1	*Total*

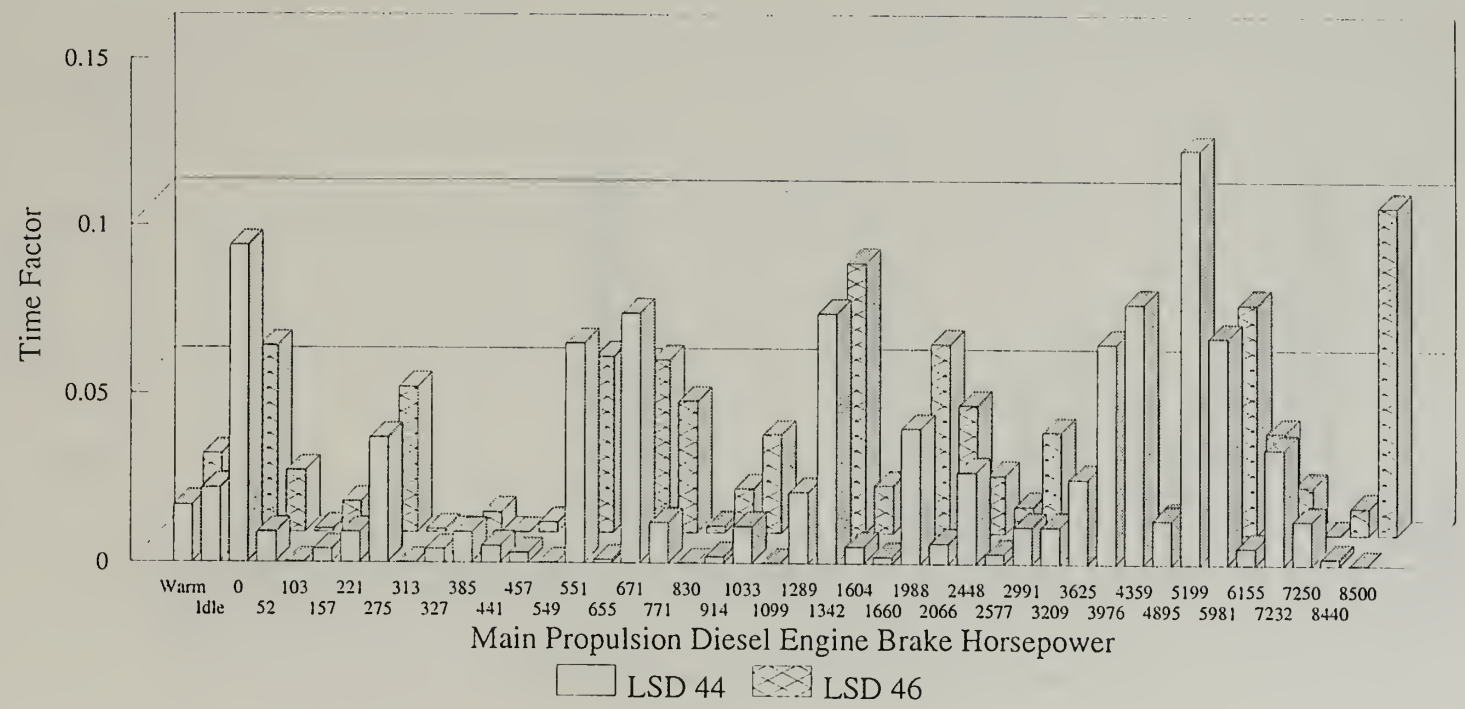

Figure B-9: East Coast Ship MPE Operating Profiles

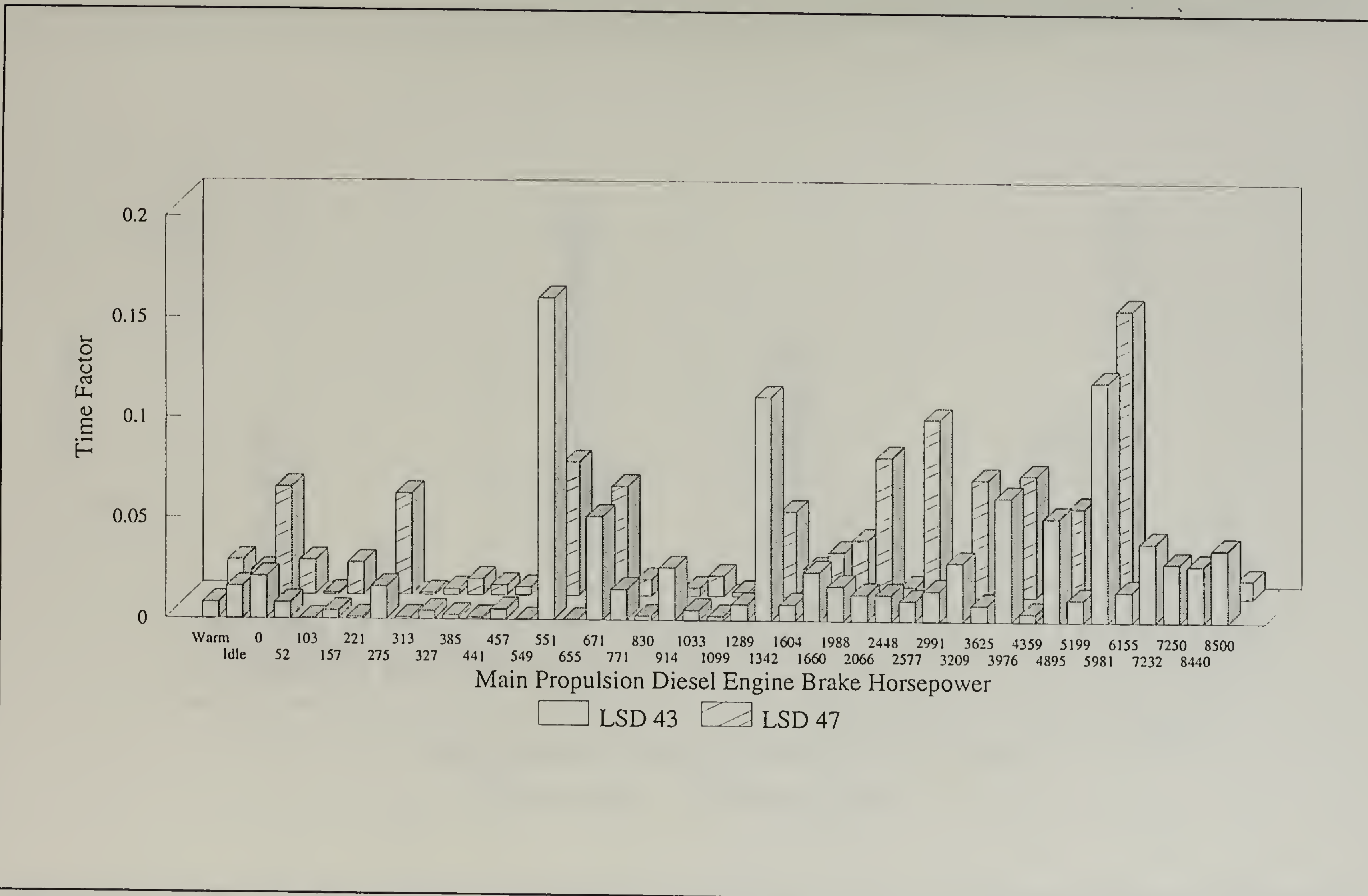

Figure B-10: West Coast Ship MPE Operating Profiles

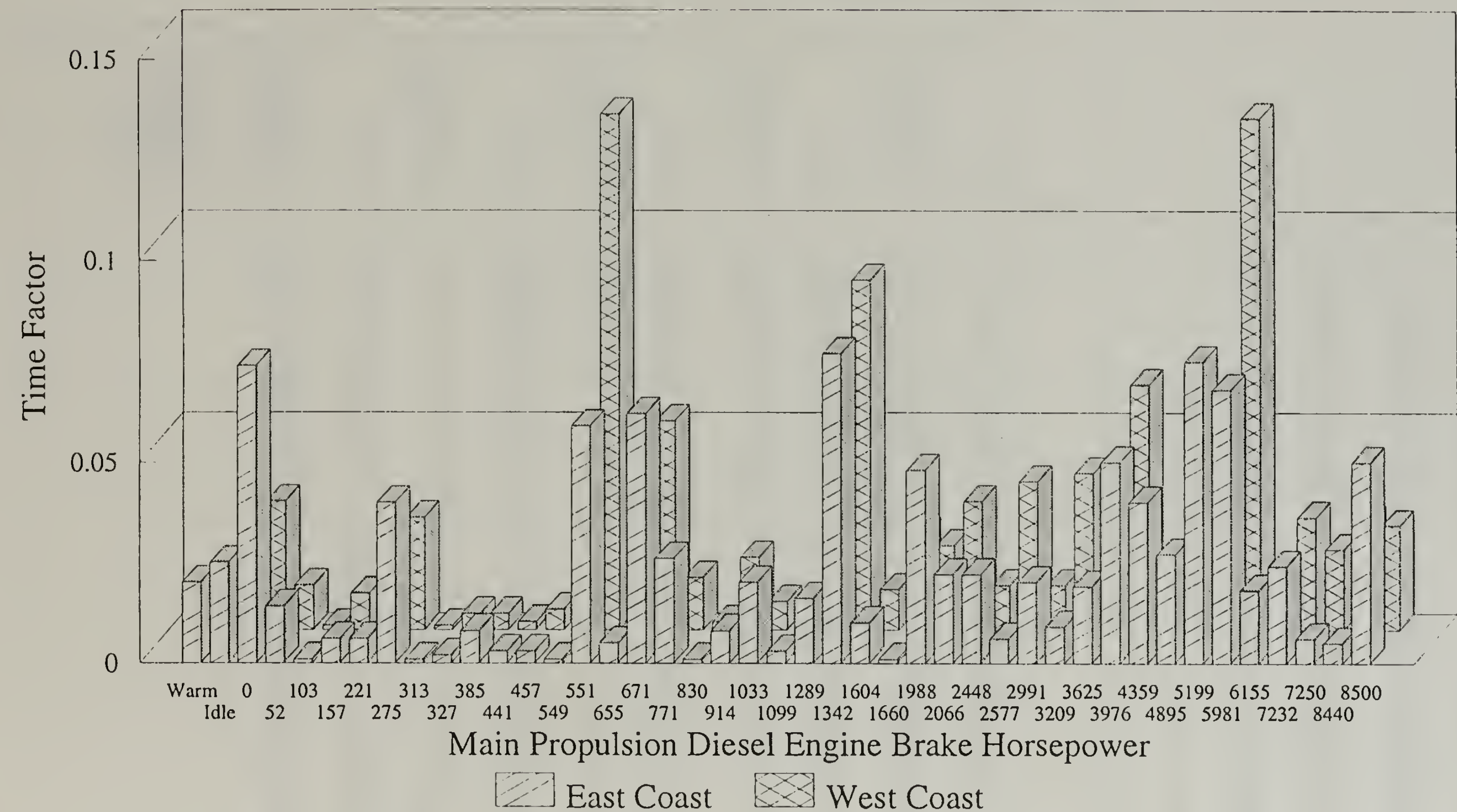

Figure B-11: East versus West Coast Ship MPE Operating Profiles

Table B-7: LSD 41 Class MPE Composite Summary

MPE Time Factor Calculations	LSD 43	LSD 43_n	LSD 44	LSD 44_n	LSD 46	LSD 46_n	LSD 47	LSD 47_n	Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
Data Points:	5011		2816		4267		3013		15107							
Total Time:	252324		133052		159845		145517		690738							
Time Secured:	74589		54499		76872		51025		256985							
Time Running:	177735	1	78553	1	82973	1	94492	1	433753	1						
Time Warming Up:	1458	0.008	1306	0.017	1892	0.023	1571	0.017	6227	0.014						
Time at Idle:	2886	0.016	1725	0.022	2357	0.028	1155	0.012	8123	0.019						
Time at Power:	173391	0.976	75522	0.961	78724	0.949	91766	0.971	419403	0.967						
											Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
	1458	0.008	1306	0.017	1892	0.023	1571	0.017	6227	0.014			200	0.385	Warm	0
	2886	0.016	1725	0.022	2357	0.028	1155	0.012	8123	0.019			200	0.385	Idle	0
	3765	0.021	7369	0.094	4537	0.055	5011	0.053	20682	0.048	All Stop	0	201	0.387	0	0
	1437	0.008	676	0.009	1515	0.018	1642	0.017	5270	0.012	2	2	201	0.387	52	0.006
	70	0	5	0	122	0.001	106	0.001	303	0.001	1	2	201	0.387	103	0.012
	797	0.004	288	0.004	724	0.009	1522	0.016	3331	0.008	2	3	201	0.387	157	0.018
	124	0.001	668	0.009	264	0.003	230	0.002	1286	0.003	2	4	201	0.387	221	0.026
	2914	0.016	2910	0.037	3580	0.043	4720	0.05	14124	0.033	2	5	201	0.387	275	0.032
	228	0.001	38	0	117	0.001	56	0.001	439	0.001	1	3	201	0.387	313	0.037
	750	0.004	278	0.004	32	0	272	0.003	332	0.003	2	6	201	0.387	327	0.038
	363	0.002	733	0.009	510	0.006	711	0.008	2317	0.005	2	7	201	0.387	385	0.045
	128	0.001	392	0.005	22	0	478	0.005	1020	0.002	1	4	201	0.387	441	0.052
	877	0.005	228	0.003	244	0.003	410	0.004	1759	0.004	2	8	201	0.387	457	0.054
	0	0	0	0	188	0.002	954	0.01	1142	0.003	2	9	201	0.387	549	0.065
	28459	0.16	5138	0.065	4313	0.052	6267	0.066	44177	0.102	1	5	201	0.387	551	0.065
	53	0	86	0.001	714	0.009	1260	0.013	2113	0.005	1	6	201	0.387	655	0.077
	9015	0.051	5786	0.074	4265	0.051	5105	0.054	24171	0.056	2	10	207	0.398	671	0.079
	2677	0.015	936	0.012	3212	0.039	742	0.008	7567	0.017	1	7	201	0.387	771	0.091
	428	0.002	0	0	204	0.002	76	0.001	708	0.002	2	11	229	0.44	830	0.098
	4651	0.026	158	0.002	1108	0.013	368	0.004	6285	0.014	1	8	201	0.387	914	0.108
	880	0.005	850	0.011	2380	0.029	916	0.01	5026	0.012	2	12	251	0.483	1033	0.122
	283	0.002	0	0	442	0.005	214	0.002	939	0.002	1	9	201	0.387	1099	0.129
	1347	0.008	1650	0.021	1012	0.012	418	0.004	4427	0.01	2	13	276	0.531	1289	0.152
	19791	0.111	5850	0.074	6647	0.08	3929	0.042	36217	0.083	1	10	207	0.398	1342	0.158
	1499	0.008	384	0.005	1152	0.014	1350	0.014	4385	0.01	2	14	298	0.573	1604	0.189
	4297	0.024	118	0.002	44	0.001	2116	0.022	6575	0.015	1	11	229	0.44	1660	0.195
	2955	0.017	3156	0.04	4631	0.056	2674	0.028	13416	0.031	2	15	320	0.615	1988	0.234
	2250	0.013	445	0.006	3118	0.038	6475	0.069	12288	0.028	1	12	251	0.483	2066	0.243
	2387	0.013	2154	0.027	1392	0.017	506	0.005	6439	0.015	2	16	342	0.658	2448	0.288
	1805	0.01	245	0.003	662	0.008	8271	0.088	10983	0.025	1	13	276	0.531	2577	0.303
	2707	0.015	844	0.011	2466	0.03	384	0.004	6401	0.015	2	17	364	0.7	2991	0.352
	5173	0.029	878	0.011	569	0.007	5481	0.058	12101	0.028	1	14	298	0.573	3209	0.378
	1448	0.008	1956	0.025	1100	0.013	296	0.003	4800	0.011	2	18	386	0.742	3625	0.426
	10861	0.061	5087	0.065	3018	0.036	5716	0.06	24682	0.057	1	15	320	0.615	3976	0.468
	768	0.004	6048	0.077	426	0.005	28	0	7270	0.017	2	19	408	0.785	4359	0.513
	9053	0.051	1037	0.013	3392	0.041	4128	0.044	17610	0.041	1	16	342	0.658	4895	0.576
	1970	0.011	9630	0.123	2528	0.03	512	0.005	14640	0.034	2	20	433	0.833	5199	0.612
	21150	0.119	5290	0.067	5661	0.068	13475	0.143	45576	0.105	1	17	370	0.712	5981	0.704
	2736	0.015	416	0.005	2488	0.03	808	0.009	6448	0.015	2	21	455	0.875	6155	0.724
	6920	0.039	2640	0.034	1192	0.014	772	0.008	11524	0.027	2	22	477	0.917	7232	0.851
	5135	0.029	1009	0.013	2	0	196	0.002	6342	0.015	1	18	382	0.735	7250	0.853
	4920	0.028	148	0.002	684	0.008	2314	0.024	8066	0.019	2	23	498	0.958	8440	0.993
	6320	0.036	0	0	8057	0.097	857	0.009	15234	0.035	2	24	520	1	8500	1
Total:	177735	1	78555	1	82983	1	94492	1	433765	1						

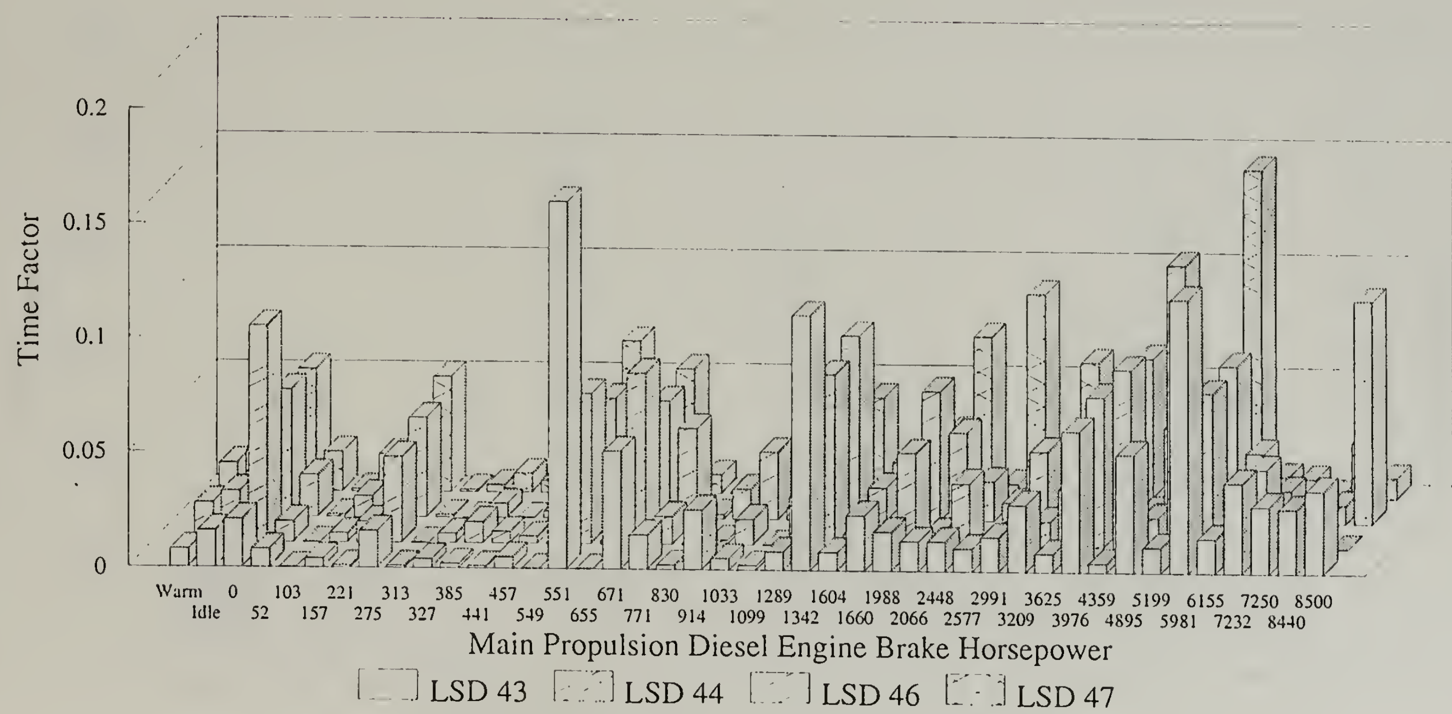

Figure B-12: Individual Ship MPE Operating Profiles

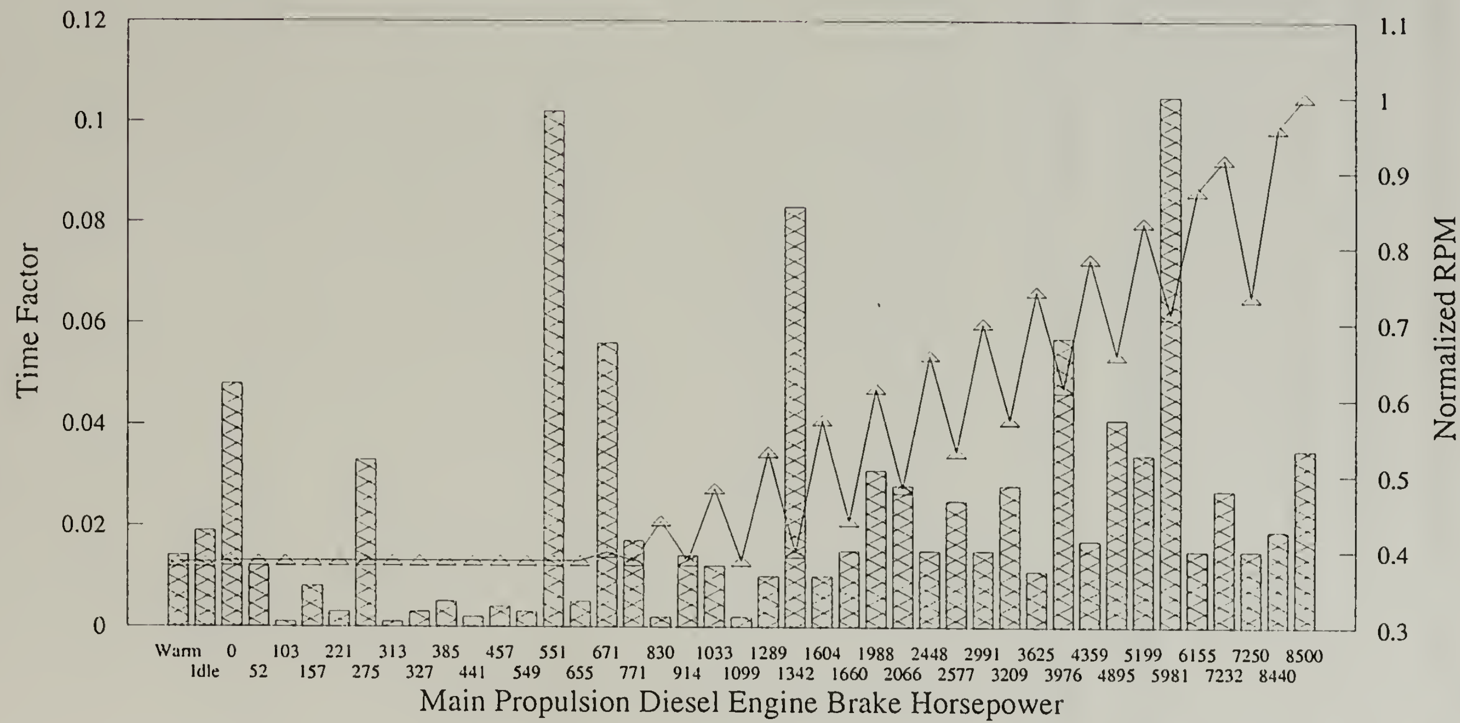

Figure B-13: LSD 41 Class Composite Ship Operating Profile

Appendix C: MPE Emission Prediction Data

This appendix provides the data used to make engine duty cycle emission predictions made in Chapter4. Section C-1 data for the Colt-Pielstick PC4-2B formed the basis for emission contour plots derived from *The Motor Ship* article of August 1992. "_n" in this section indicate Power Fraction and RPM Factor from equations 16 and 17.

Section C-2 gives duty cycle emission prediction spreadsheet pages based on linear interpolation of emission contour maps provided as Section C-3.

NOx g/kW-h	RPM_d	Power_d	NOx Level g/bhp-h	RPM	Power	RPM_n	Power_n		CO g/kW-h	RPM_d	Power_d	CO Level g/bhp-h	RPM	Power	RPM_n	Power_n
10	3.38	4.3	7.457	407	1274	1.035	1.075		1.1	3.5	4.1	0.82027	415	1215	1.075	1.025
10	3.6	4	7.457	421	1185	1.105	1		1.1	3.35	4	0.82027	406	1185	1.03	1
10	3.8	3.72	7.457	433	1102	1.165	0.93		1.1	3.31	3.9	0.82027	403	1156	1.015	0.975
10	3.91	3.56	7.457	440	1055	1.2	0.89		1.1	3.3	3.85	0.82027	402	1141	1.01	0.963
10	4.11	3.26	7.457	452	966	1.26	0.815		1.1	3.3	3.5	0.82027	402	1037	1.01	0.875
10	4.37	2.8	7.457	468	830	1.34	0.7		1.1	3.4	3.1	0.82027	409	919	1.045	0.775
									1.1	3.45	3	0.82027	412	889	1.06	0.75
16	0	1.56	11.9312	200	462	0	0.39		1.1	3.6	2.83	0.82027	421	839	1.105	0.708
16	0.326	1.3	11.9312	220	385	0.1	0.325		1.1	3.8	2.76	0.82027	433	818	1.165	0.69
16	0.9	1	11.9312	255	296	0.275	0.25		1.1	3.9	2.8	0.82027	439	830	1.195	0.7
16	1.2	0.9	11.9312	274	267	0.37	0.225		1.1	3.96	3	0.82027	443	889	1.215	0.75
16	1.6	0.87	11.9312	298	258	0.49	0.218		1.1	3.93	3.3	0.82027	441	978	1.205	0.825
16	1.9	0.9	11.9312	317	267	0.585	0.225		1.1	3.91	3.5	0.82027	440	1037	1.2	0.875
16	2.06	1	11.9312	326	296	0.63	0.25		1.1	3.8	3.96	0.82027	433	1173	1.165	0.99
16	2.2	1.1	11.9312	335	326	0.675	0.275		1.1	3.79	4	0.82027	433	1185	1.165	1
16	2.28	1.3	11.9312	340	385	0.7	0.325		1.1	3.6	4.09	0.82027	421	1212	1.105	1.023
16	2.3	1.4	11.9312	341	415	0.705	0.35		1.1	3.5	4.1	0.82027	415	1215	1.075	1.025
16	2.3	1.5	11.9312	341	444	0.705	0.375									
16	2.25	1.7	11.9312	338	504	0.69	0.425		1.2	3	4.4	0.89484	384	1304	0.92	1.1
16	2.1	1.96	11.9312	329	581	0.645	0.49		1.2	2.91	3.92	0.89484	379	1161	0.895	0.98
16	1.9	2.2	11.9312	317	652	0.585	0.55		1.2	2.9	3.65	0.89484	378	1081	0.89	0.913
16	1.47	2.5	11.9312	290	741	0.45	0.625		1.2	3	3.1	0.89484	384	919	0.92	0.775
16	1.14	2.68	11.9312	270	794	0.35	0.67		1.2	3.1	2.7	0.89484	390	800	0.95	0.675
									1.2	3.2	2.5	0.89484	396	741	0.98	0.625
12	-0.5	0.8	8.9484	169	237	-0.155	0.2		1.2	3.25	2.4	0.89484	399	711	0.995	0.6
12	0.4	0.5	8.9484	225	148	0.125	0.125		1.2	3.4	2.3	0.89484	409	681	1.045	0.575
12	0.6	0.42	8.9484	237	124	0.185	0.105		1.2	3.5	2.3	0.89484	415	681	1.075	0.575
12	1.1	0.32	8.9484	267	95	0.335	0.08		1.2	3.6	2.31	0.89484	421	684	1.105	0.578
12	1.6	0.21	8.9484	298	62	0.49	0.053		1.2	3.9	2.45	0.89484	439	726	1.195	0.613
12	2.1	0.17	8.9484	329	50	0.645	0.043									
12	2.5	0.13	8.9484	353	39	0.765	0.033		1.4	1.16	1	1.04398	271	296	0.355	0.25
12	2.6	0.14	8.9484	360	41	0.8	0.035		1.4	1.15	0.95	1.04398	271	281	0.355	0.238
12	3.1	0.2	8.9484	390	59	0.95	0.05		1.4	1.3	0.9	1.04398	280	267	0.4	0.225
12	3.6	0.36	8.9484	421	107	1.105	0.09		1.4	1.6	0.9	1.04398	298	267	0.49	0.225
12	3.9	0.5	8.9484	439	148	1.195	0.125		1.4	2.6	0.92	1.04398	360	273	0.8	0.23
12	4.1	0.93	8.9484	452	276	1.26	0.233		1.4	2.7	0.94	1.04398	366	279	0.83	0.235
12	4.2	1.2	8.9484	458	356	1.29	0.3		1.4	2.75	1	1.04398	369	296	0.845	0.25
12	4.2	1.7	8.9484	458	504	1.29	0.425		1.4	2.7	1.06	1.04398	366	314	0.83	0.265
12	4.1	2	8.9484	452	593	1.26	0.5		1.4	2.6	1.1	1.04398	360	326	0.8	0.275
12	3.8	2.6	8.9484	433	770	1.165	0.65		1.4	2.1	1.12	1.04398	329	332	0.645	0.28
12	3.6	2.9	8.9484	421	859	1.105	0.725		1.4	1.8	1.1	1.04398	310	326	0.55	0.275
12	3.1	3.35	8.9484	390	993	0.95	0.838		1.4	1.6	1.08	1.04398	298	320	0.49	0.27
12	2.8	3.6	8.9484	372	1067	0.86	0.9		1.4	1.5	1.05	1.04398	292	311	0.46	0.263
12	2.61	3.72	8.9484	360	1102	0.8	0.93		1.4	1.3	1.03	1.04398	280	305	0.4	0.258
12	1.96	4.04	8.9484	320	1197	0.6	1.01		1.4	1.16	1	1.04398	271	296	0.355	0.25
12	1.3	4.32	8.9484	280	1280	0.4	1.08									
									1.5	0.1	0.4	1.11855	206	119	0.03	0.1
14	-0.33	1.3	10.4398	180	385	-0.1	0.325		1.5	0.35	0.5	1.11855	221	148	0.105	0.125
14	0.33	1	10.4398	220	296	0.1	0.25		1.5	0.6	0.57	1.11855	237	169	0.185	0.143
14	0.8	0.8	10.4398	249	237	0.245	0.2		1.5	0.8	0.6	1.11855	249	178	0.245	0.15
14	1.1	0.7	10.4398	267	207	0.335	0.175		1.5	1.1	0.65	1.11855	267	193	0.335	0.163
14	1.6	0.58	10.4398	298	172	0.49	0.145		1.5	1.6	0.7	1.11855	298	207	0.49	0.175
14	2.1	0.5	10.4398	329	148	0.645	0.125		1.5	2.1	0.7	1.11855	329	207	0.645	0.175
14	2.6	0.54	10.4398	360	160	0.8	0.135		1.5	2.4	0.71	1.11855	347	210	0.735	0.178
14	2.9	0.62	10.4398	378	184	0.89	0.155		1.5	2.5	0.73	1.11855	353	216	0.765	0.183
14	3.1	0.72	10.4398	390	213	0.95	0.18		1.5	2.6	0.75	1.11855	360	222	0.8	0.188
14	3.35	1	10.4398	406	296	1.03	0.25		1.5	2.8	0.82	1.11855	372	243	0.86	0.205
14	3.43	1.2	10.4398	410	356	1.05	0.3		1.5	2.94	0.9	1.11855	380	267	0.9	0.225

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14	3.48	1.4	10.4398	413	415	1.065	0.35		1.5	3.05	1	1.11855	387	296	0.935	0.25
14	3.5	1.5	10.4398	415	444	1.075	0.375		1.5	3.08	1.05	1.11855	389	311	0.945	0.263
14	3.4	1.85	10.4398	409	548	1.045	0.463		1.5	3	1.18	1.11855	384	350	0.92	0.295
14	3.2	2.2	10.4398	396	652	0.98	0.55		1.5	2.8	1.2	1.11855	372	356	0.86	0.3
14	2.9	2.5	10.4398	378	741	0.89	0.625		1.5	1.6	1.2	1.11855	298	356	0.49	0.3
14	2.6	2.73	10.4398	360	809	0.8	0.683		1.5	1.3	1.12	1.11855	280	332	0.4	0.28
14	2.2	3	10.4398	335	889	0.675	0.75		1.5	0.98	1.08	1.11855	260	320	0.3	0.27
14	1.79	3.2	10.4398	310	948	0.55	0.8		1.5	0.65	1.04	1.11855	240	308	0.2	0.26
14	1.3	3.4	10.4398	280	1007	0.4	0.85		1.5	0	0.88	1.11855	200	261	0	0.22
									1.5	-0.65	0.72	1.11855	160	213	-0.2	0.18
									1.5	2.28	4.2	1.11855	340	1244	0.7	1.05
									1.5	2.35	3.6	1.11855	344	1067	0.72	0.9
									1.5	2.41	3.2	1.11855	348	948	0.74	0.8
									1.5	2.5	2.8	1.11855	353	830	0.765	0.7
									1.5	2.6	2.4	1.11855	360	711	0.8	0.6
									1.5	2.7	2	1.11855	366	593	0.83	0.5
									1.5	2.93	1.5	1.11855	380	444	0.9	0.375
									1.5	3.1	1.32	1.11855	390	391	0.95	0.33
									1.5	3.35	1.22	1.11855	406	361	1.03	0.305
									1.5	3.6	1.3	1.11855	421	385	1.105	0.325
									1.5	3.9	1.4	1.11855	439	415	1.195	0.35
									2	0.95	0.32	1.4914	258	95	0.29	0.08
									2	1.1	0.35	1.4914	267	104	0.335	0.088
									2	1.4	0.45	1.4914	286	133	0.43	0.113
									2	1.6	0.49	1.4914	298	145	0.49	0.123
									2	1.7	0.5	1.4914	304	148	0.52	0.125
									2	2.1	0.5	1.4914	329	148	0.645	0.125
									2	2.3	0.5	1.4914	341	148	0.705	0.125
									2	2.4	0.52	1.4914	347	154	0.735	0.13
									2	2.6	0.54	1.4914	360	160	0.8	0.135
									2	2.9	0.6	1.4914	378	178	0.89	0.15
									2	3.3	0.7	1.4914	402	207	1.01	0.175
									2	3.6	0.8	1.4914	421	237	1.105	0.2
									2	3.9	0.92	1.4914	439	273	1.195	0.23
									2	-0.16	1.28	1.4914	190	379	-0.05	0.32
									2	0.65	1.23	1.4914	240	364	0.2	0.308
									2	1.3	1.21	1.4914	280	359	0.4	0.303
									2	1.8	1.27	1.4914	310	376	0.55	0.318
									2	2.1	1.3	1.4914	329	385	0.645	0.325
									2	2.3	1.32	1.4914	341	391	0.705	0.33
									2	2.5	1.42	1.4914	353	421	0.765	0.355
									2	2.6	1.55	1.4914	360	459	0.8	0.388
									2	2.63	1.7	1.4914	361	504	0.805	0.425
									2	2.6	1.8	1.4914	360	533	0.8	0.45
									2	2.55	2	1.4914	356	593	0.78	0.5
									2	2.4	2.4	1.4914	347	711	0.735	0.6
									2	2.28	2.8	1.4914	340	830	0.7	0.7
									2	2.11	3.2	1.4914	329	948	0.645	0.8
									2	1.96	3.6	1.4914	320	1067	0.6	0.9
									2	1.63	4.4	1.4914	300	1304	0.5	1.1
									2.5	0	1.5	1.86425	200	444	0	0.375
									2.5	0.65	1.4	1.86425	240	415	0.2	0.35
									2.5	1.3	1.36	1.86425	280	403	0.4	0.34
									2.5	1.8	1.36	1.86425	310	403	0.55	0.34
									2.5	2.1	1.4	1.86425	329	415	0.645	0.35
									2.5	2.25	1.5	1.86425	338	444	0.69	0.375
									2.5	2.3	1.6	1.86425	341	474	0.705	0.4
									2.5	2.32	1.7	1.86425	342	504	0.71	0.425
									2.5	2.3	1.78	1.86425	341	527	0.705	0.445
									2.5	2.2	1.9	1.86425	335	563	0.675	0.475
									2.5	1.96	2.1	1.86425	320	622	0.6	0.525
									2.5	0.98	2.72	1.86425	260	806	0.3	0.68

HC g/kW-h	RPM	Power	HC Level g/bhp-h	RPM	Power	RPM_n	Power_n
0.4	-0.33	0.72	0.29828	180	213	-0.1	0.18
0.4	0.3	0.85	0.29828	218	252	0.09	0.213
0.4	0.6	0.93	0.29828	237	276	0.185	0.233
0.4	0.8	1	0.29828	249	296	0.245	0.25
0.4	1.1	1.12	0.29828	267	332	0.335	0.28
0.4	1.6	1.36	0.29828	298	403	0.49	0.34
0.4	1.85	1.5	0.29828	313	444	0.565	0.375
0.4	2.1	1.68	0.29828	329	498	0.645	0.42
0.4	2.48	2	0.29828	352	593	0.76	0.5
0.4	2.6	2.12	0.29828	360	628	0.8	0.53
0.4	2.94	2.5	0.29828	380	741	0.9	0.625
0.4	3.1	2.72	0.29828	390	806	0.95	0.68
0.4	3.25	3	0.29828	399	889	0.995	0.75
0.4	3.41	3.5	0.29828	409	1037	1.045	0.875
0.4	3.51	4	0.29828	415	1185	1.075	1
0.4	3.53	4.2	0.29828	417	1244	1.085	1.05
0.5	-0.33	0.64	0.37285	180	190	-0.1	0.16
0.5	0.3	0.76	0.37285	218	225	0.09	0.19
0.5	0.6	0.85	0.37285	237	252	0.185	0.213
0.5	1.1	1	0.37285	267	296	0.335	0.25
0.5	1.6	1.15	0.37285	298	341	0.49	0.288
0.5	2.1	1.32	0.37285	329	391	0.645	0.33
0.5	2.5	1.5	0.37285	353	444	0.765	0.375
0.5	3.1	1.8	0.37285	390	533	0.95	0.45
0.5	3.42	2	0.37285	410	593	1.05	0.5
0.5	3.6	2.13	0.37285	421	631	1.105	0.533
0.5	3.8	2.3	0.37285	433	681	1.165	0.575
0.8	-0.33	0.36	0.59656	180	107	-0.1	0.09
0.8	0.3	0.45	0.59656	218	133	0.09	0.113
0.8	0.6	0.5	0.59656	237	148	0.185	0.125
0.8	1.1	0.58	0.59656	267	172	0.335	0.145
0.8	1.6	0.7	0.59656	298	207	0.49	0.175
0.8	2.1	0.8	0.59656	329	237	0.645	0.2
0.8	2.6	0.92	0.59656	360	273	0.8	0.23
0.8	2.85	1	0.59656	375	296	0.875	0.25
0.8	3.1	1.08	0.59656	390	320	0.95	0.27
0.8	3.6	1.22	0.59656	421	361	1.105	0.305
0.8	3.8	1.34	0.59656	433	397	1.165	0.335
1	-0.33	0.28	0.7457	180	83	-0.1	0.07
1	0.2	0.29	0.7457	212	86	0.06	0.073
1	0.6	0.32	0.7457	237	95	0.185	0.08
1	1.1	0.396	0.7457	267	117	0.335	0.099
1	1.6	0.5	0.7457	298	148	0.49	0.125
1	2.1	0.58	0.7457	329	172	0.645	0.145
1	2.6	0.68	0.7457	360	201	0.8	0.17
1	3.1	0.78	0.7457	390	231	0.95	0.195
1	3.6	0.9	0.7457	421	267	1.105	0.225
1	3.8	1	0.7457	433	296	1.165	0.25
2	2.3	0.32	1.4914	341	95	0.705	0.08
2	2.6	0.38	1.4914	360	113	0.8	0.095
2	3.1	0.42	1.4914	390	124	0.95	0.105
2	3.6	0.52	1.4914	421	154	1.105	0.13
2	3.8	0.6	1.4914	433	178	1.165	0.15

CO2 g/kW-h	RPM	Power	CO2 Level g/bhp-h	RPM	Power	RPM_n	Power_n
585	3.25	4.3	436.2345	399	1274	0.995	1.075
585	3.57	4	436.2345	419	1185	1.095	1
585	3.6	3.96	436.2345	421	1173	1.105	0.99
585	3.9	3.56	436.2345	439	1055	1.195	0.89
585	1.8	2.15	436.2345	310	637	0.55	0.538
585	2.1	2.11	436.2345	329	625	0.645	0.528
585	2.6	2.1	436.2345	360	622	0.8	0.525
585	3.1	2.15	436.2345	390	637	0.95	0.538
585	3.6	2.32	436.2345	421	687	1.105	0.58
585	3.77	2.5	436.2345	431	741	1.155	0.625
585	3.9	2.7	436.2345	439	800	1.195	0.675
575	2.1	3.1	428.7775	329	919	0.645	0.775
575	2.35	3	428.7775	344	889	0.72	0.75
575	2.6	2.89	428.7775	360	856	0.8	0.723
575	2.9	2.78	428.7775	378	824	0.89	0.695
575	3.1	2.75	428.7775	390	815	0.95	0.688
575	3.2	2.75	428.7775	396	815	0.98	0.688
575	3.3	2.78	428.7775	402	824	1.01	0.695
575	3.4	2.8	428.7775	409	830	1.045	0.7
575	3.5	2.85	428.7775	415	844	1.075	0.713
575	3.55	3	428.7775	418	889	1.09	0.75
575	3.55	3.1	428.7775	418	919	1.09	0.775
575	3.5	3.17	428.7775	415	939	1.075	0.793
575	3.4	3.3	428.7775	409	978	1.045	0.825
575	3.15	3.5	428.7775	393	1037	0.965	0.875
575	2.9	3.6	428.7775	378	1067	0.89	0.9
600	1.2	1.37	447.42	274	406	0.37	0.343
600	1.6	1.38	447.42	298	409	0.49	0.345
600	2.1	1.43	447.42	329	424	0.645	0.358
600	2.6	1.48	447.42	360	439	0.8	0.37
600	3.1	1.62	447.42	390	480	0.95	0.405
600	3.6	1.78	447.42	421	527	1.105	0.445
600	3.9	2	447.42	439	593	1.195	0.5
635	-0.1	0.4	473.5195	194	119	-0.03	0.1
635	0.1	0.42	473.5195	206	124	0.03	0.105
635	0.6	0.45	473.5195	237	133	0.185	0.113
635	1.1	0.5	473.5195	267	148	0.335	0.125
635	1.6	0.58	473.5195	298	172	0.49	0.145
635	2.1	0.64	473.5195	329	190	0.645	0.16
635	2.6	0.72	473.5195	360	213	0.8	0.18
635	3.1	0.85	473.5195	390	252	0.95	0.213
635	3.6	1.01	473.5195	421	299	1.105	0.253
635	3.9	1.15	473.5195	439	341	1.195	0.288
800	1.1	0.11	596.56	267	33	0.335	0.028
800	1.6	0.18	596.56	298	53	0.49	0.045
800	2.1	0.2	596.56	329	59	0.645	0.05
800	2.6	0.28	596.56	360	83	0.8	0.07
800	3.1	0.35	596.56	390	104	0.95	0.088
800	3.6	0.45	596.56	421	133	1.105	0.113
800	3.9	0.6	596.56	439	178	1.195	0.15

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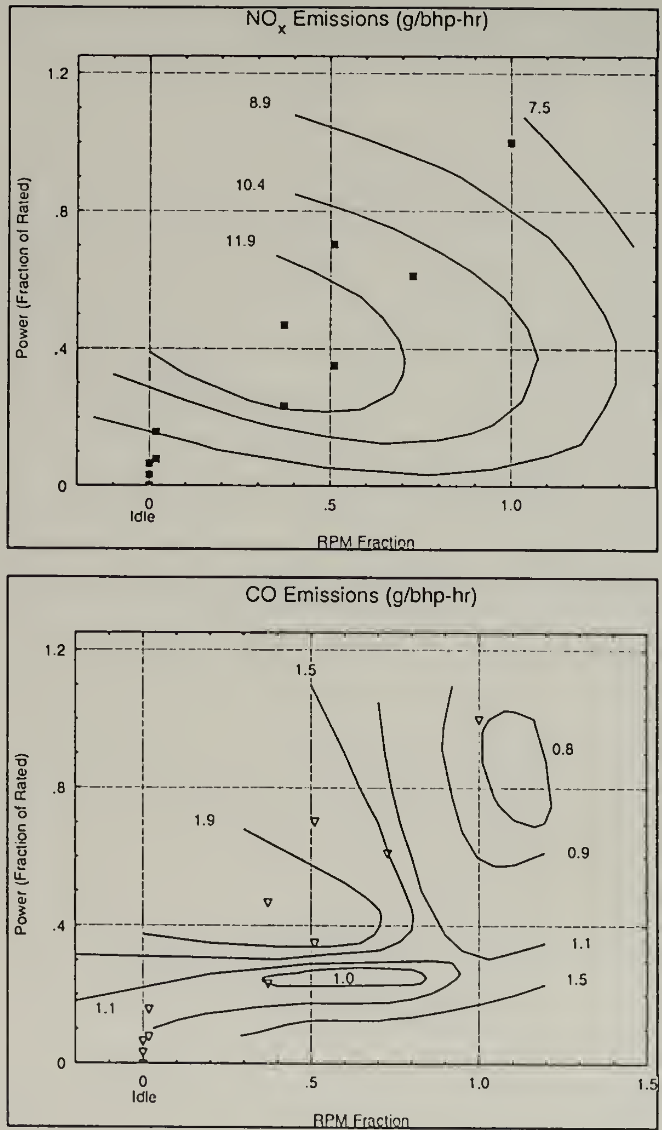
DUTY CYCLE COMPARISON													
	Rated Speed	RPM Factor	Percent Load	Time Factor	NOx	NOx Time	CO	CO Time	HC	HC Time	CO2	CO2 Time	Japanese NOx Factor
ISO 8178-4 E3 Duty Cycle													
	0.630	0.630	0.250	0.150	11.9	1.785	1	0.15	0.52	0.078	462	69.3	2.304
	0.800	0.800	0.500	0.150	11.1	1.665	1.37	0.206	0.32	0.048	437	65.55	2.197
	0.910	0.910	0.750	0.500	9.7	4.85	0.91	0.455	0.27	0.135	422	211	7.139
	1.000	1.000	1.000	0.200	8	1.6	0.82	0.164	0.23	0.046	435	87	2.802
			Total	1		9.9		0.975		0.307		432.85	14.442
ISO 8178-4 E1 Duty Cycle													
	Idle	0	0.000	0.400	0.31	0.124	2	0.8	2	0.8	580	232	6.784
	0.400	0.400	0.250	0.250	12	3	1	0.25	0.42	0.105	460	115	4.207
	0.600	0.600	0.500	0.150	12	1.8	1.91	0.287	0.225	0.034	437	65.55	2.327
	0.600	0.600	0.750	0.140	10.6	1.484	1.6	0.224	0.15	0.021	430	60.2	2.172
	1.000	1.000	1.000	0.060	8	0.48	0.82	0.049	0.23	0.014	435	26.1	0.841
			Total	1		6.888		1.61		0.974		498.85	16.331
U.S. Navy Endurance Test													
	1.000	1.000	1.000	0.255	8	2.041	0.82	0.209	0.23	0.059	435	110.969	3.574
	1.000	1.000	0.850	0.128	8.6	1.097	0.81	0.103	0.28	0.036	429	54.719	1.787
	Idle	0.000	0.000	0.021	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	1.000	1.000	1.000	0.234	8	1.869	0.82	0.192	0.23	0.054	435	101.648	3.274
	Idle	0.000	0.000	0.021	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	0.750	0.750	0.500	0.064	11.2	0.72	1.6	0.103	0.3	0.019	437	28.093	0.954
	Idle	0.000	0.000	0.021	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	1.000	1.000	0.850	0.021	8.6	0.184	0.81	0.017	0.28	0.006	429	9.193	0.3
	1.000	1.000	1.100	0.234	7.5	1.753	0.85	0.199	0.26	0.061	437	102.115	3.274
			Total	1		7.685		0.952		0.364		444.024	14.252
ICOMIA 36-88 Duty Cycle													
	Idle	0.000	0.000	0.400	0.31	0.124	2	0.8	2	0.8	580	232	6.784
	0.400	0.400	0.253	0.250	12	3	1	0.25	0.42	0.105	460	115	4.207
	0.600	0.600	0.465	0.150	12.1	1.815	2	0.3	0.25	0.038	439	65.85	2.327
	0.800	0.800	0.716	0.140	10.2	1.428	1.05	0.147	0.218	0.031	429	60.06	2.051
	1.000	1.000	1.000	0.060	8	0.48	0.82	0.049	0.23	0.014	435	26.1	0.841
			Total	1		6.847		1.546		0.988		499.01	16.21
Japanese Heavy-Duty Diesel													
	Idle	0.000	0.000	0.051	0.31	0.016	2	0.103	2	0.103	580	29.853	0.873
	0.400	0.400	1.000	0.104	9.5	0.992	1.65	0.172	0.8	0.084	429	44.793	1.757
	0.400	0.400	0.250	0.087	12	1.041	1	0.087	0.42	0.036	460	39.912	1.46
	0.600	0.600	1.000	0.157	9	1.416	1.3	0.205	0.1	0.016	433	68.134	2.441
	0.600	0.600	0.250	0.179	12	2.153	1	0.179	0.42	0.075	460	82.529	2.784
	0.800	0.800	0.750	0.421	10	4.206	1.05	0.442	0.225	0.095	425	178.75	6.161
			Total	1		9.824		1.188		0.409		443.971	15.476
U.S. EPA 13-Mode Duty Cycle													
	Idle	0.000	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
	0.200	0.200	0.020	0.080	2.1	0.168	1.7	0.136	1.7	0.136	597	47.76	1.546
	0.400	0.400	0.250	0.080	12	0.96	1	0.08	0.42	0.034	460	36.8	1.346
	0.600	0.600	0.500	0.080	12	0.96	1.91	0.153	0.225	0.018	437	34.96	1.241
	0.800	0.800	0.750	0.080	10	0.8	1.05	0.084	0.225	0.018	428	34.24	1.172
	1.000	1.000	1.000	0.080	8	0.64	0.82	0.066	0.23	0.018	435	34.8	1.121
	Idle	0.000	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
	1.000	1.000	1.000	0.080	8	0.64	0.82	0.066	0.23	0.018	435	34.8	1.121
	1.000	1.000	0.750	0.080	9.3	0.744	0.85	0.068	0.3	0.024	428	34.24	1.121
	1.000	1.000	0.500	0.080	10.5	0.84	0.99	0.079	0.39	0.031	440	35.2	1.121
	1.000	1.000	0.250	0.080	10.5	0.84	1.3	0.104	0.64	0.051	473	37.84	1.121
	1.000	1.000	0.020	0.080	8.5	0.68	3	0.24	3	0.24	615	49.2	1.121
	Idle	0.000	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
			Total	1		7.335		1.478		0.99		496.42	15.439

CARB 8-Mode Duty Cycle													
	Idle	0	0	0.05	0.31	0.016	2	0.1	2	0.1	580	29	0.848
	1	1	0.75	0.15	9.3	1.395	0.85	0.128	0.3	0.045	428	64.2	2.101
	1	1	0.5	0.15	10.5	1.575	0.99	0.149	0.39	0.059	440	66	2.101
	Idle	0	0	0.05	0.31	0.016	2	0.1	2	0.1	580	29	0.848
	Max Torque	0.85	1	0.15	8.5	1.275	0.95	0.143	0.21	0.032	432	64.8	2.171
	Max Torque	0.85	0.75	0.15	10	1.5	1	0.15	0.25	0.038	428	64.2	2.171
	Max Torque	0.85	0.5	0.15	10.9	1.635	1.09	0.164	0.35	0.053	437	65.55	2.171
	Max Torque	0.85	0.3	0.15	11.1	1.665	1.1	0.165	0.52	0.078	460	69	2.171
			Total	1		9.077		1.099		0.505		451.75	14.582
LSD Class 1 Engine/Shaft													
	0.387	0	0.012	0.001	0.9	0.001	1.8	0.002	1.8	0.002	579	0.579	0.017
	0.387	0	0.037	0.001	3.6	0.004	1.5	0.002	1.28	0.001	536	0.536	0.017
	0.387	0	0.052	0.002	4.7	0.009	1.4	0.003	1.13	0.002	527	1.054	0.034
	0.387	0	0.065	0.102	6	0.612	1.2	0.122	0.84	0.086	510	52.02	1.728
	0.387	0	0.077	0.005	6.5	0.033	1.1	0.006	0.7	0.004	502	2.51	0.085
	0.387	0	0.091	0.017	6.8	0.116	1.08	0.018	0.65	0.011	490	8.33	0.288
	0.387	0	0.108	0.014	7	0.098	1.07	0.015	0.6	0.008	473	6.622	0.237
	0.387	0	0.129	0.002	8	0.016	1.06	0.002	0.5	0.001	472	0.944	0.034
	0.398	0.018	0.158	0.083	8.9	0.739	1.04	0.086	0.45	0.037	470	39.01	1.398
	0.44	0.086	0.195	0.015	9.6	0.144	1.04	0.016	0.38	0.006	465	6.975	0.248
	0.483	0.157	0.243	0.028	10.5	0.294	1.1	0.031	0.27	0.008	460	12.88	0.454
	0.531	0.235	0.303	0.025	12	0.3	1.5	0.038	0.21	0.005	453	11.325	0.398
	0.573	0.303	0.378	0.028	13.4	0.375	2	0.056	0.18	0.005	446	12.488	0.438
	0.615	0.372	0.468	0.057	13.4	0.764	2.1	0.12	0.17	0.01	442	25.194	0.88
	0.658	0.442	0.576	0.041	12.1	0.496	2	0.082	0.16	0.007	436	17.876	0.625
	0.7	0.511	0.704	0.105	11.1	1.166	1.7	0.179	0.15	0.016	433	45.465	1.58
	0.735	0.568	0.853	0.015	10	0.15	1.6	0.024	0.15	0.002	429	6.435	0.224
	0.75	0.592	1	0	8.9	0	1.3	0	0.14	0	410	0	0
LSD Class 2 Engine/Shaft			*Total*	0.541		5.317		0.802		0.211		250.243	8.685
	0.387	0	0	0.081	0.31	0.025	2	0.162	2	0.162	580	46.98	1.372
	0.387	0.000	0.006	0.012	0.63	0.008	1.9	0.023	1.86	0.022	571	6.852	0.203
	0.387	0.000	0.018	0.008	1.1	0.009	1.8	0.014	1.71	0.014	563	4.504	0.136
	0.387	0.000	0.026	0.003	2	0.006	1.7	0.005	1.57	0.005	554	1.662	0.051
	0.387	0.000	0.032	0.033	3.1	0.102	1.6	0.053	1.42	0.047	545	17.985	0.559
	0.387	0.000	0.038	0.003	3.5	0.011	1.5	0.005	1.28	0.004	536	1.608	0.051
	0.387	0.000	0.052	0.002	4.7	0.009	1.4	0.003	1.13	0.002	527	1.054	0.034
	0.387	0.000	0.054	0.004	4.9	0.02	1.3	0.005	0.99	0.004	519	2.076	0.068
	0.387	0.000	0.065	0.003	6	0.018	1.2	0.004	0.84	0.003	510	1.53	0.051
	0.398	0.018	0.079	0.056	6.5	0.364	1.2	0.067	0.7	0.039	500	28	0.943
	0.44	0.086	0.098	0.002	8	0.016	1.2	0.002	0.69	0.001	480	0.96	0.033
	0.483	0.157	0.122	0.012	8.9	0.107	1.2	0.014	0.65	0.008	473	5.676	0.194
	0.531	0.235	0.152	0.01	9.7	0.097	1.1	0.011	0.6	0.006	471	4.71	0.159
	0.573	0.303	0.189	0.01	10.4	0.104	1.05	0.011	0.55	0.006	466	4.66	0.157
	0.615	0.372	0.234	0.031	11.9	0.369	1	0.031	0.49	0.015	460	14.26	0.479
	0.658	0.442	0.288	0.015	12.3	0.185	1.1	0.017	0.44	0.007	451	6.765	0.229
	0.7	0.511	0.352	0.015	12.6	0.189	2	0.03	0.39	0.006	447	6.705	0.226
	0.742	0.579	0.426	0.011	12.3	0.135	2.1	0.023	0.3	0.003	442	4.862	0.164
	0.785	0.649	0.513	0.017	11.8	0.201	1.85	0.031	0.26	0.004	437	7.429	0.25
	0.833	0.728	0.612	0.034	10.8	0.367	1.5	0.051	0.24	0.008	433	14.722	0.494
	0.875	0.796	0.724	0.015	10.2	0.153	1.06	0.016	0.24	0.004	429	6.435	0.216
	0.917	0.865	0.851	0.027	9.1	0.246	0.94	0.025	0.23	0.006	428	11.556	0.385
	0.958	0.931	0.993	0.019	8.2	0.156	0.87	0.017	0.23	0.004	433	8.227	0.268
	1	1	1	0.035	8	0.28	0.82	0.029	0.23	0.008	435	15.225	0.49
			Total	0.458		3.177		0.649		0.388		224.443	7.212
			Class Total	0.999		8.494		1.451		0.599		475	15.897

LSD Class Duty Cycle													
	Idle	0	0.000	0.083	0.31	0.026	2	0.166	2	0.166	580	48.14	1.408
	0.387	0	0.065	0.064	6	0.384	1.2	0.077	0.84	0.054	510	32.64	1.084
	0.387	0	0.032	0.128	3.1	0.397	1.6	0.205	1.42	0.182	545	69.76	2.169
	0.398	0.018	0.078	0.141	6.5	0.917	1.2	0.169	0.7	0.099	500	70.5	2.375
	0.398	0.018	0.158	0.077	8.9	0.685	1.04	0.08	0.45	0.035	470	36.19	1.297
	0.615	0.372	0.234	0.109	11.9	1.297	1	0.109	0.49	0.053	460	50.14	1.683
	0.615	0.372	0.468	0.051	13.4	0.683	2.1	0.107	0.17	0.009	442	22.542	0.787
	0.700	0.511	0.704	0.040	11.1	0.444	1.7	0.068	0.15	0.006	433	17.32	0.602
	0.700	0.511	0.352	0.160	12.6	2.016	2	0.32	0.39	0.062	447	71.52	2.407
	0.833	0.728	0.612	0.093	10.8	1.004	1.5	0.14	0.24	0.022	433	40.269	1.351
	1.000	1	1.000	0.054	8	0.432	0.82	0.044	0.23	0.012	435	23.49	0.756
			Total	1		8.285		1.485		0.7		483	15.919
T-AO 187 Class													
	Idle	0	0	0.083	0.31	0.026	2	0.166	2	0.166	580	48	1.408
	0.5	0	0.001	0.002	0.35	0.001	2	0.004	2	0.004	580	1	0.034
	0.5	0	0.002	0.011	0.3	0.003	1.9	0.021	1.9	0.021	580	6	0.187
	0.5	0	0.003	0.009	0.45	0.004	1.9	0.017	1.9	0.017	579	5	0.153
	0.5	0	0.004	0.007	0.5	0.004	1.9	0.013	1.8	0.013	579	4	0.119
	0.5	0	0.014	0.135	0.9	0.122	1.8	0.243	1.8	0.243	579	78	2.29
	0.5	0	0.028	0.008	3	0.024	1.7	0.014	1.57	0.013	554	4	0.136
	0.5	0	0.046	0.022	4.5	0.099	1.4	0.031	1.13	0.025	527	12	0.373
	0.5	0	0.069	0.018	6.2	0.112	1.2	0.022	0.84	0.015	510	9	0.305
	0.5	0	0.095	0.005	6.8	0.034	1.07	0.005	0.65	0.003	490	2	0.085
	0.516	0.032	0.126	0.139	8.5	1.182	1.06	0.147	0.55	0.076	472	66	2.344
	0.563	0.126	0.16	0.017	9.4	0.16	1.06	0.018	0.5	0.009	468	8	0.282
	0.615	0.23	0.181	0.04	10.3	0.412	1.04	0.042	0.45	0.018	464	19	0.651
	0.668	0.336	0.235	0.035	11.9	0.417	1.01	0.035	0.42	0.015	460	16	0.56
	0.72	0.44	0.296	0.038	12.3	0.467	1.3	0.049	0.35	0.013	451	17	0.599
	0.774	0.548	0.367	0.088	12.3	1.082	1.95	0.172	0.3	0.026	446	39	1.367
	0.828	0.656	0.453	0.056	11.9	0.666	1.95	0.109	0.28	0.016	442	25	0.859
	0.876	0.752	0.558	0.12	11.1	1.332	1.5	0.18	0.27	0.032	435	52	1.82
	0.923	0.846	0.686	0.026	10.2	0.265	1	0.026	0.27	0.007	429	11	0.39
	0.975	0.95	0.841	0.087	8.9	0.774	0.86	0.075	0.25	0.022	428	37	1.291
	0.998	0.996	0.917	0.054	8.2	0.443	0.81	0.044	0.23	0.012	431	23	0.798
			Total	1		7.629		1.433		0.766		482	16.051
T-AO 187 Duty Cycle													
	Idle	0	0	0.083	0.31	0.026	2	0.166	2	0.166	580	48	1.408
	0.5	0	0.014	0.192	0.9	0.173	1.8	0.346	1.8	0.346	579	111	3.256
	0.516	0.032	0.126	0.218	8.5	1.853	1.06	0.231	0.55	0.12	472	103	3.675
	0.774	0.55	0.367	0.16	12.3	1.968	1.95	0.312	0.3	0.048	446	71	2.486
	0.876	0.76	0.558	0.293	11.1	3.252	1.5	0.44	0.27	0.079	435	127	4.443
	1	1	0.917	0.054	8	0.432	0.82	0.044	0.23	0.012	435	23	0.797
			Total	1		7.704		1.539		0.771		483	14.657

DEMA Generator Duty Cycle													
	1	1	0.5	0.2	13.6	2.72	0.9	0.18	1	0.2			2.802
	1	1	0.75	0.4	15.3	6.12	0.7	0.28	0.83	0.332			5.604
	1	1	1	0.4	18.8	7.52	0.44	0.176	0.53	0.212			5.604
			Total	1		16.36		0.636		0.744			14.01
ISO 8178-4 D1 Duty Cycle													
	1	1	0.5	0.2	13.6	2.72	0.9	0.18	1	0.2			2.802
	1	1	0.75	0.5	15.3	7.65	0.7	0.35	0.83	0.415			7.005
	1	1	1	0.3	18.8	5.64	0.44	0.132	0.53	0.159			4.203
			Total	1		16.01		0.662		0.774			14.01
ISO 8178-4 D2 Duty Cycle													
	1	1	0.1	0.1	11.4	1.14	1.75	0.175	3.7	0.37			1.401
	1	1	0.25	0.3	12.5	3.75	1.35	0.405	1.35	0.405			4.203
	1	1	0.5	0.3	13.6	4.08	0.9	0.27	1	0.3			4.203
	1	1	0.75	0.25	15.3	3.825	0.7	0.175	0.83	0.208			3.502
	1	1	1	0.05	18.8	0.94	0.44	0.022	0.53	0.027			0.7
			Total	1		13.735		1.047		1.31			14.009
LSD Class SSDG Duty Cycle													
	1	1	0	0.033	10.5	0.347	1.95	0.064	5.7	0.188			0.462
	1	1	0.4	0.2	13	2.6	1.03	0.206	1.05	0.21			2.802
	1	1	0.5	0.464	13.6	6.31	0.9	0.418	1	0.464			6.5
	1	1	0.6	0.266	14.2	3.777	0.83	0.221	0.95	0.253			3.726
	1	1	0.8	0.026	15.7	0.408	0.65	0.017	0.8	0.021			0.364
	1	1	1	0.011	18.8	0.207	0.44	0.005	0.53	0.006			0.154
			Total	1		13.649		0.931		1.142			14.008
Summary (g/bhp-hr)	NOx	Japan NOx	CO	HC	CO2								
MPE													
ISO 8178-4 E3 Duty Cycle	9.9	14.4	1	0.3	433								
ISO 8178-4 E1 Duty Cycle	6.9	16.3	1.6	1	499								
U.S. Navy Endurance Test	7.7	14.3	1	0.4	444								
ICOMIA 36-88 Duty Cycle	6.8	16.2	1.5	1	499								
Japanese Heavy-Duty Diesel	9.8	15.5	1.2	0.4	444								
U.S. EPA 13-Mode Duty Cycle	7.3	15.4	1.5	1	496								
CARB 8-Mode Duty Cycle	9.1	14.6	1.1	0.5	452								
LSD Class Propeller Curve	8.5	15.9	1.5	0.6	475								
LSD Class Duty Cycle	8.3	15.9	1.5	0.7	483								
T-AO Class Propeller Curve	7.6	16.1	1.4	0.8	482								
T-AO Class Duty Cycle	7.7	14.7	1.5	0.8	483								
SSDG													
DEMA Generator Duty Cycle	16.4	14	0.6	0.7									
ISO 8178-4 D1 Duty Cycle	16	14	0.7	0.8									
ISO 8178-4 D2 Duty Cycle	13.7	14	1	1.3									
LSD Class SSDG Duty Cycle	13.6	14	0.9	1.1									



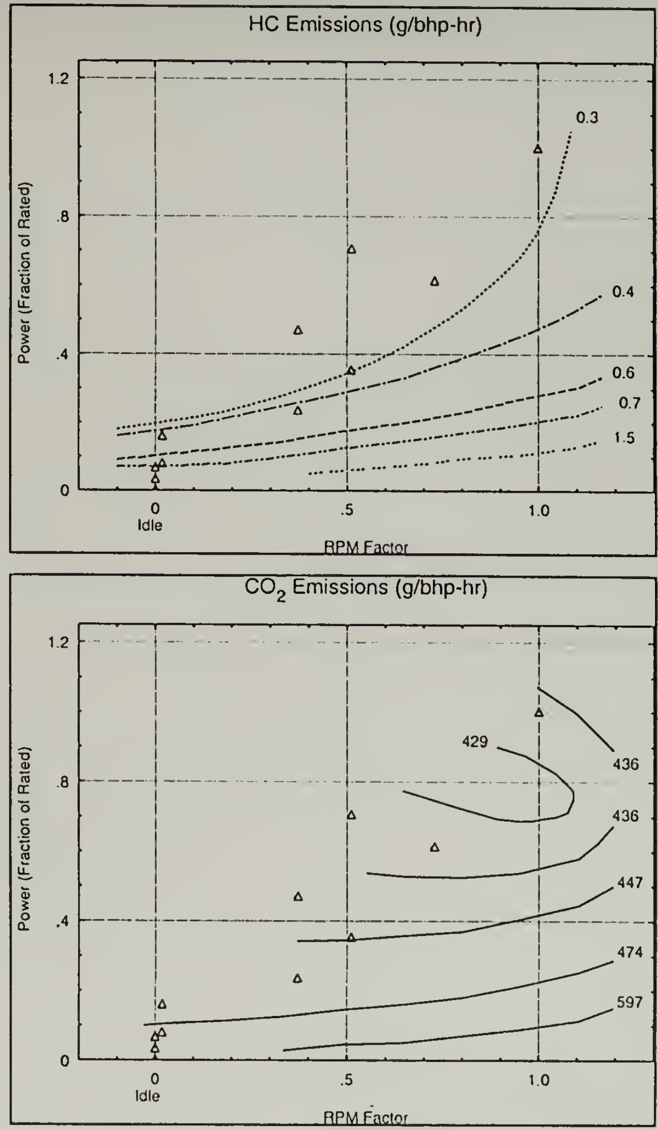


Figure C-1

LSD 41 Class Duty Cycle Emission Contour Plots

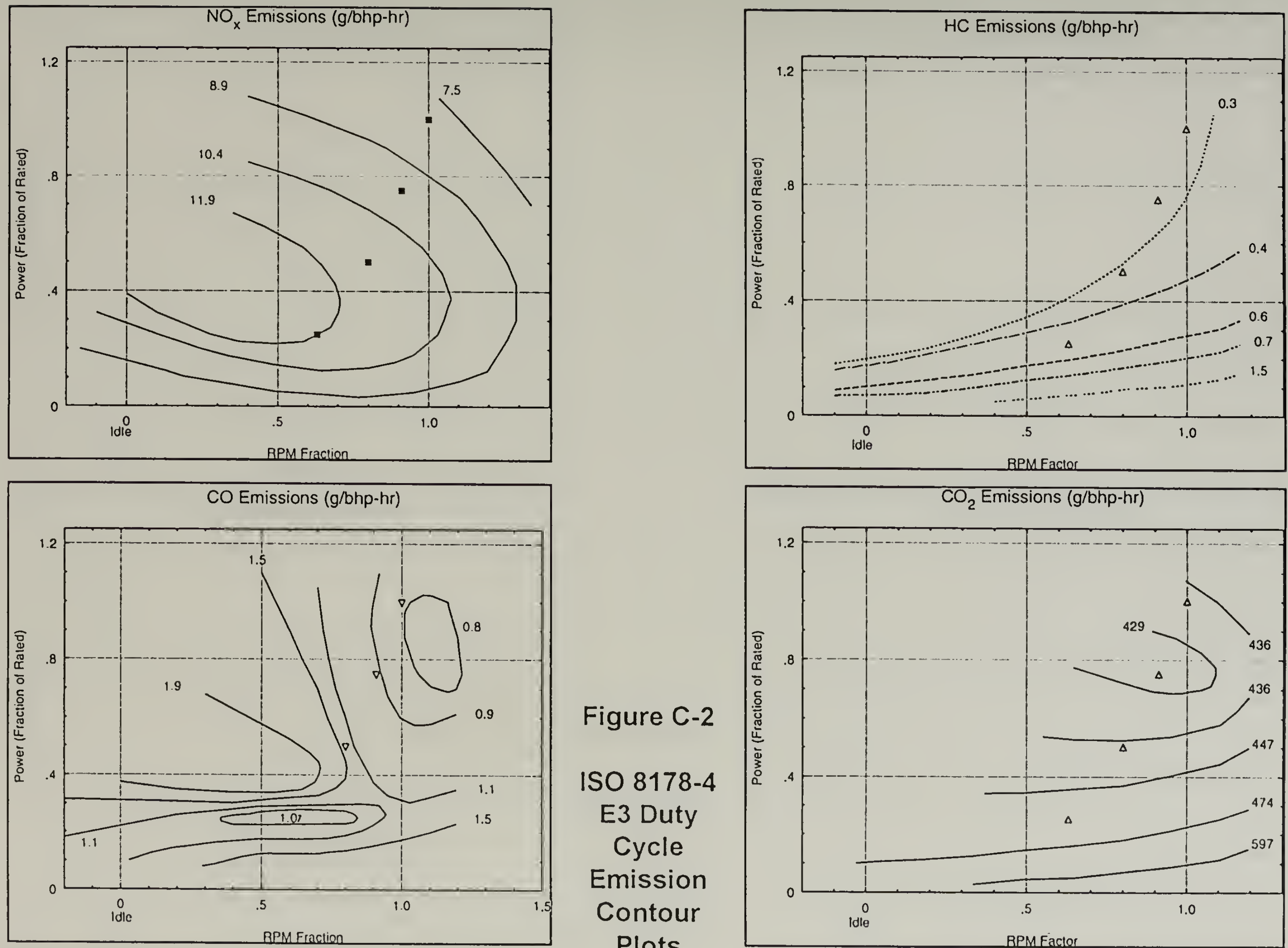


Figure C-2

ISO 8178-4 E3 Duty Cycle Emission Contour Plots

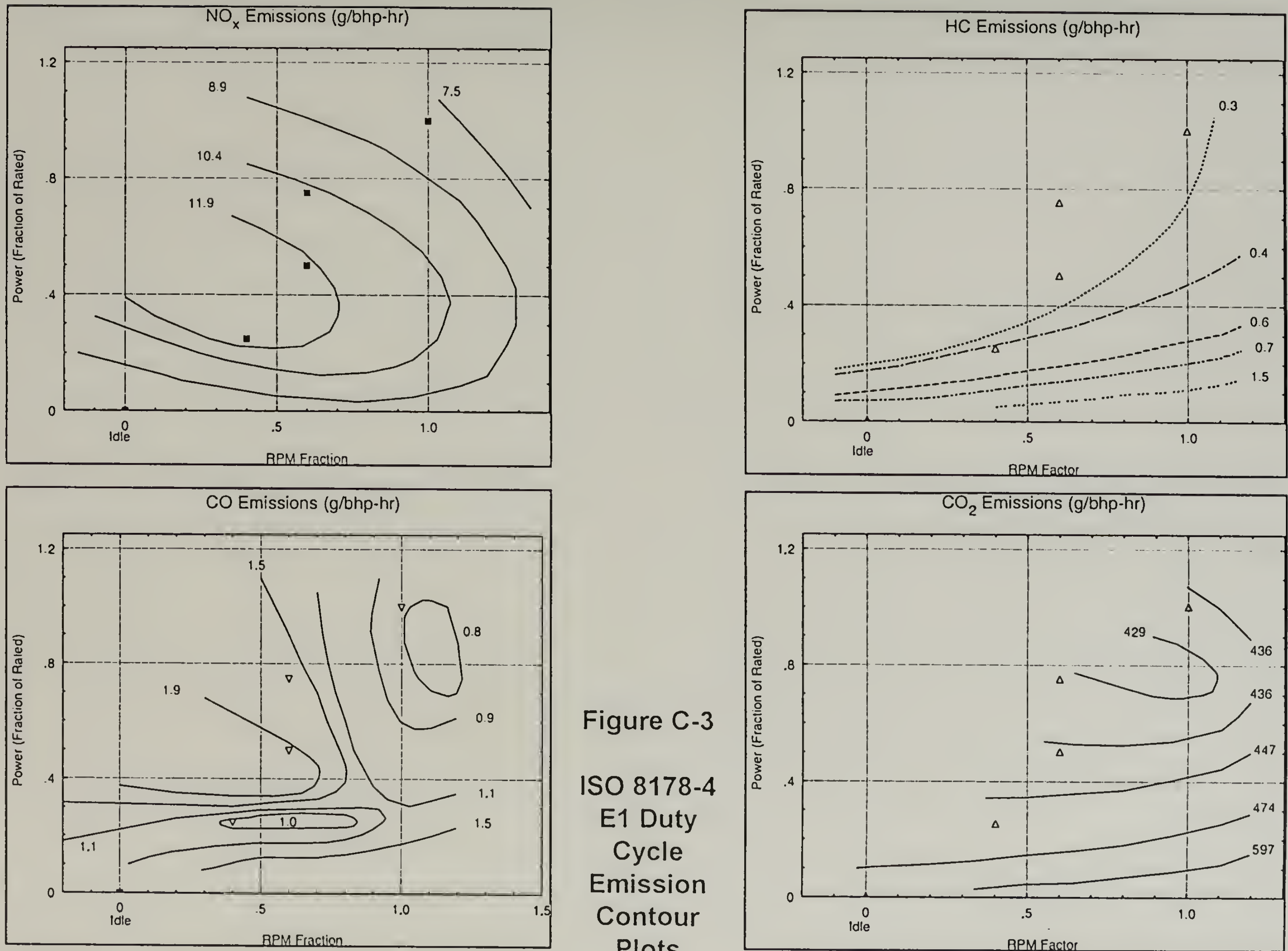
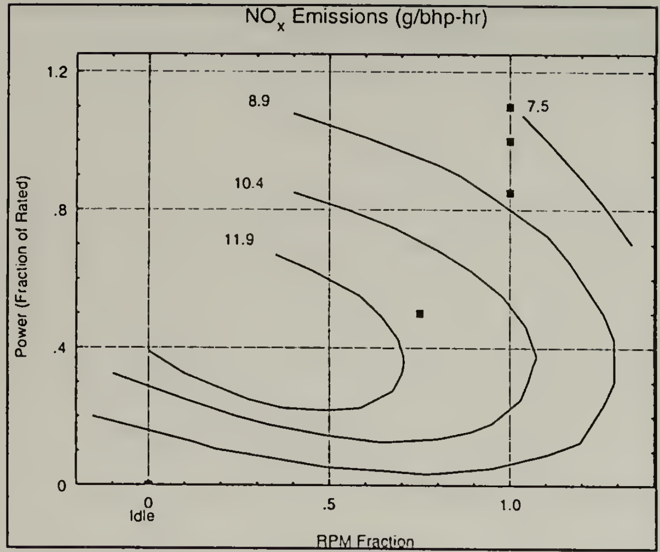
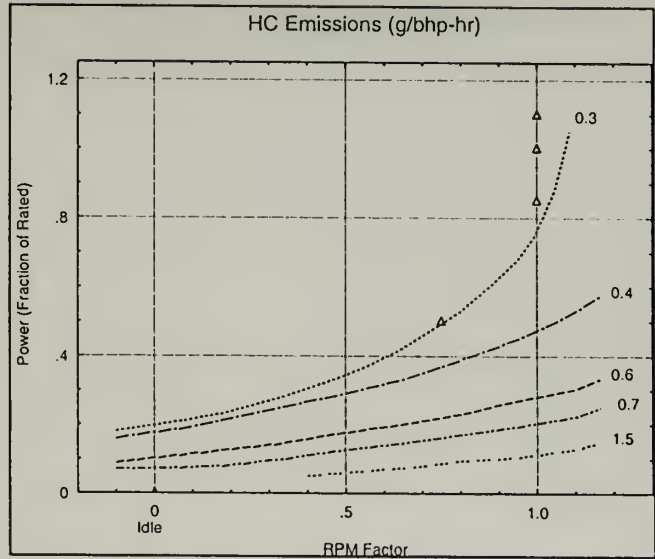
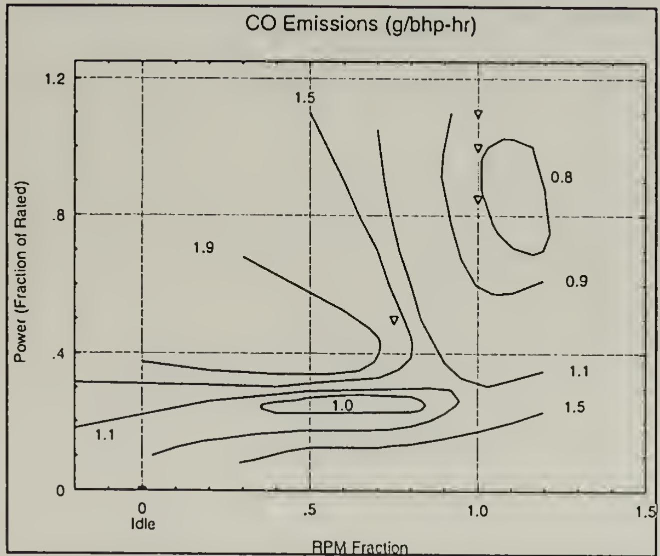


Figure C-3

ISO 8178-4 E1 Duty Cycle Emission Contour Plots







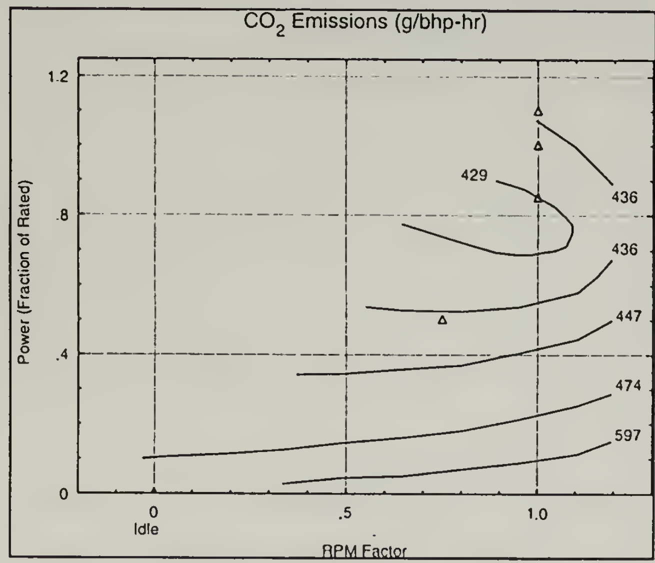


Figure C-4

U.S.N. Endurance Test Emission Contour Plots

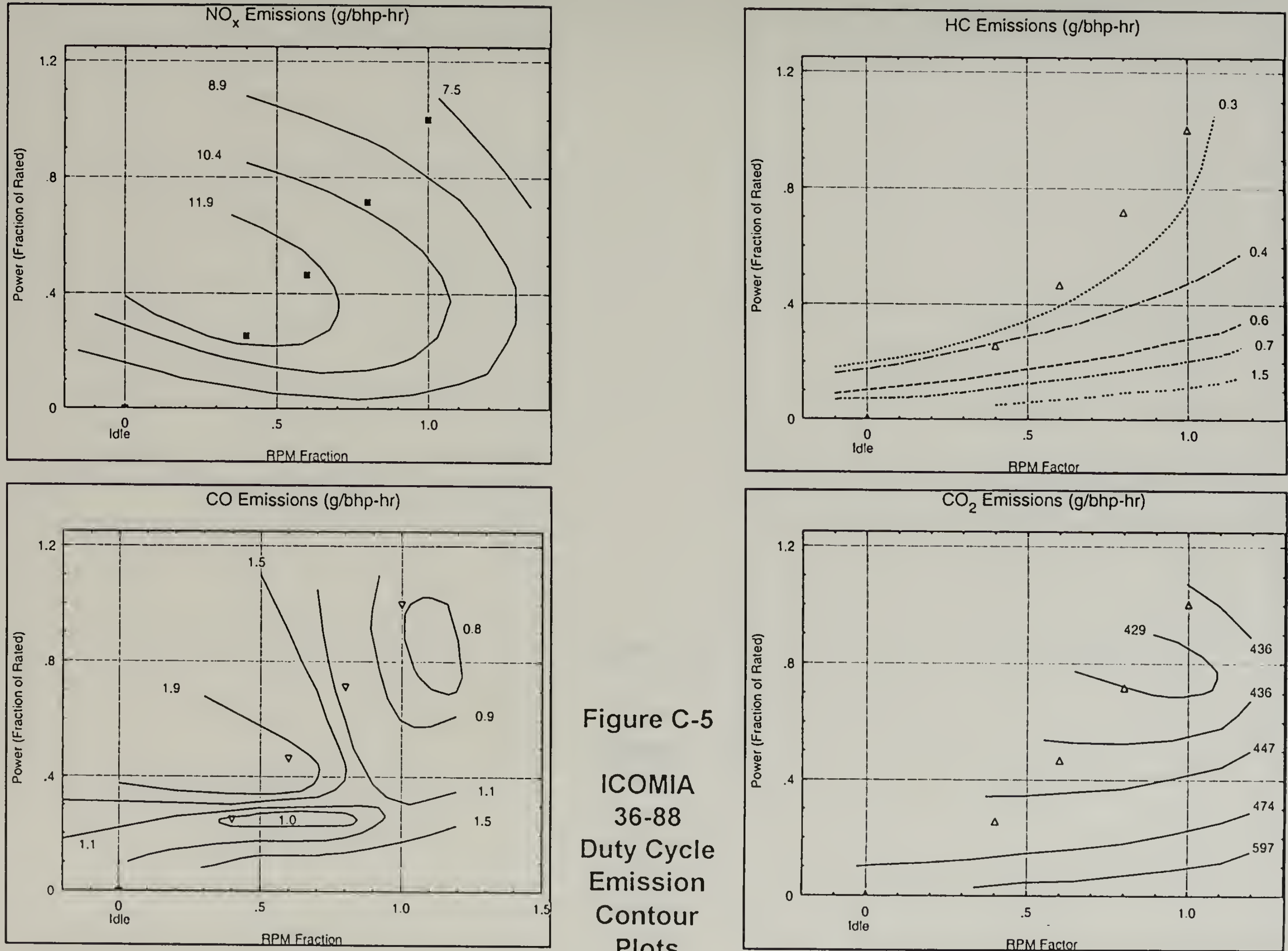
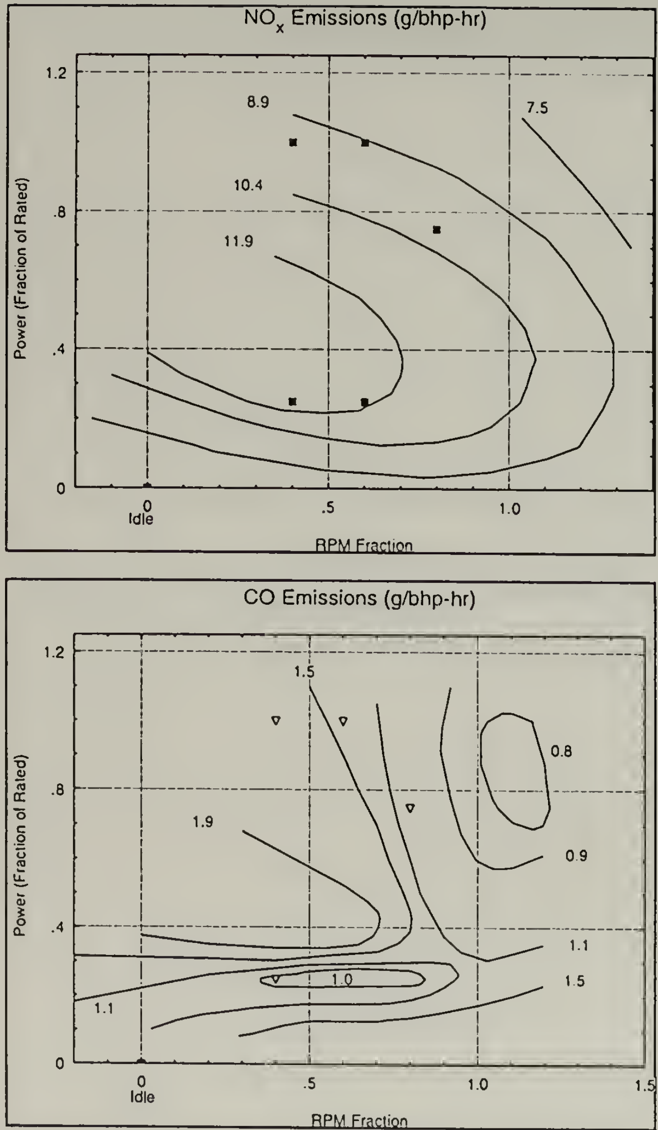


Figure C-5

ICOMIA 36-88 Duty Cycle Emission Contour Plots



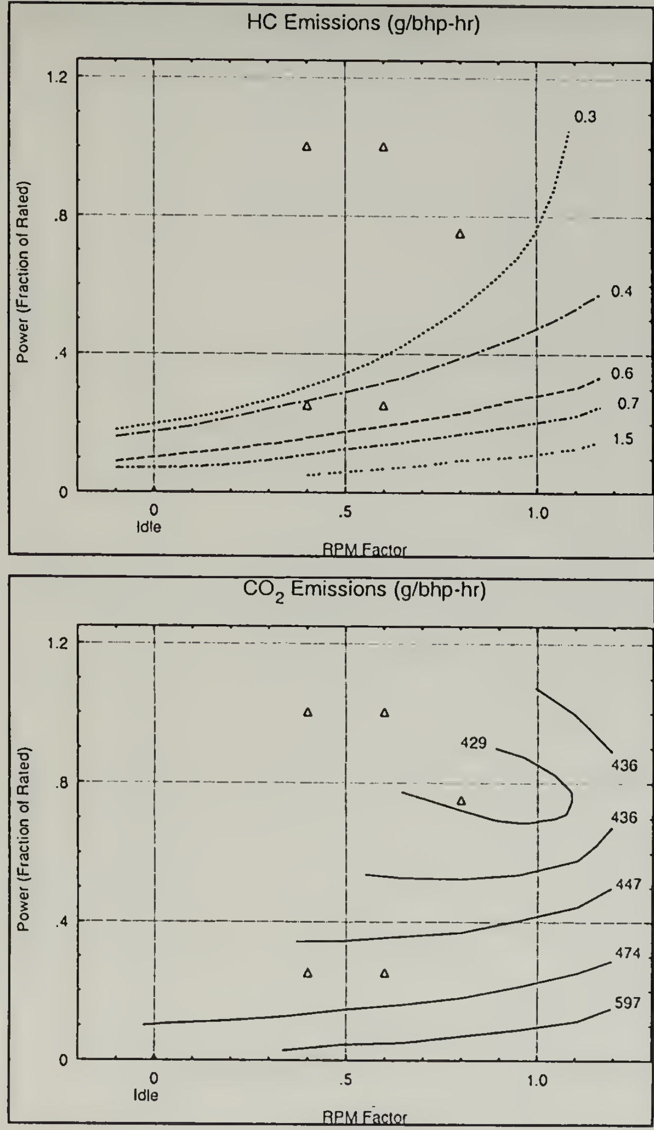


Figure C-6

Japan Heavy-Duty Diesel Duty Cycle Emission Contour Plots

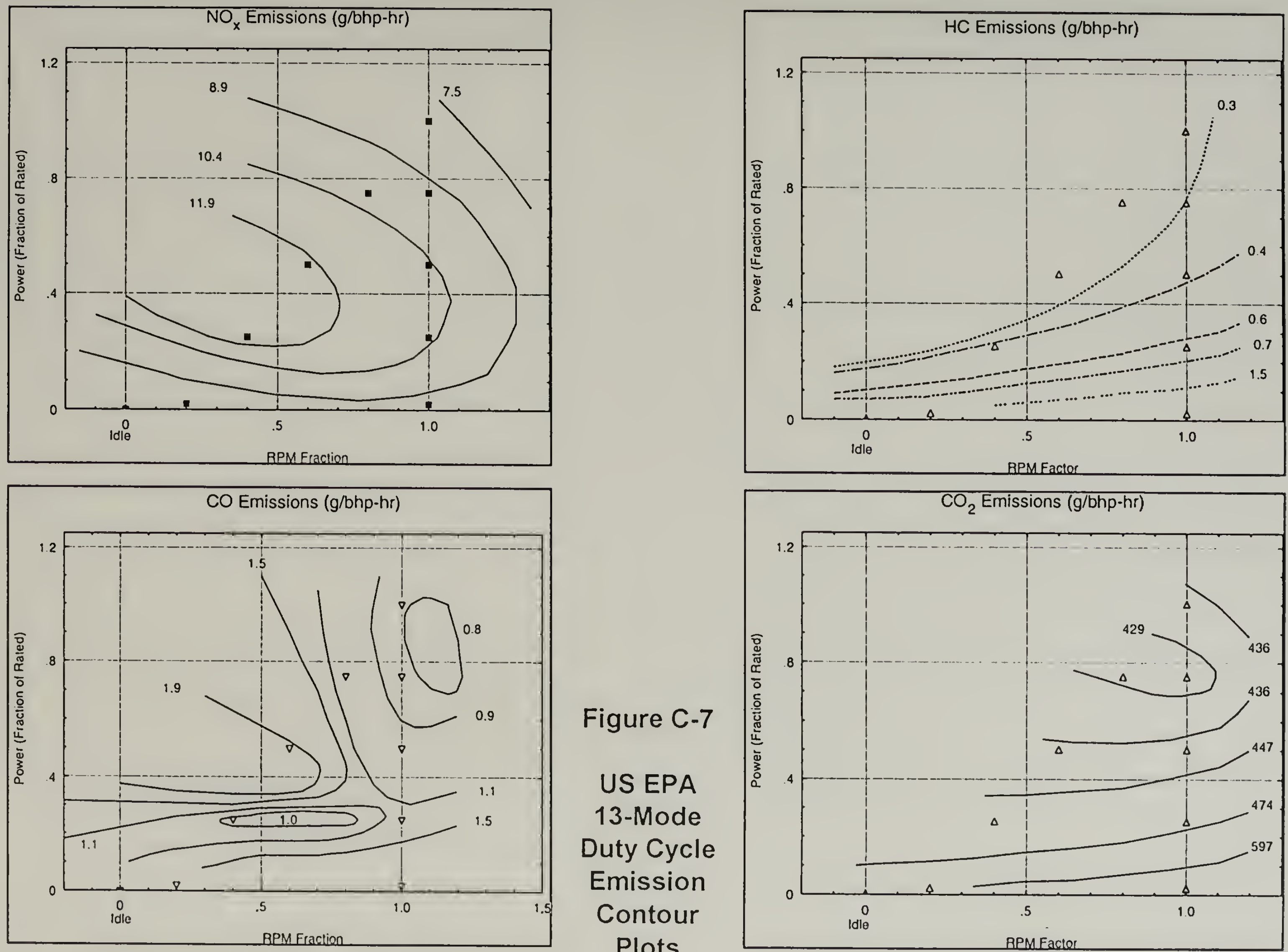
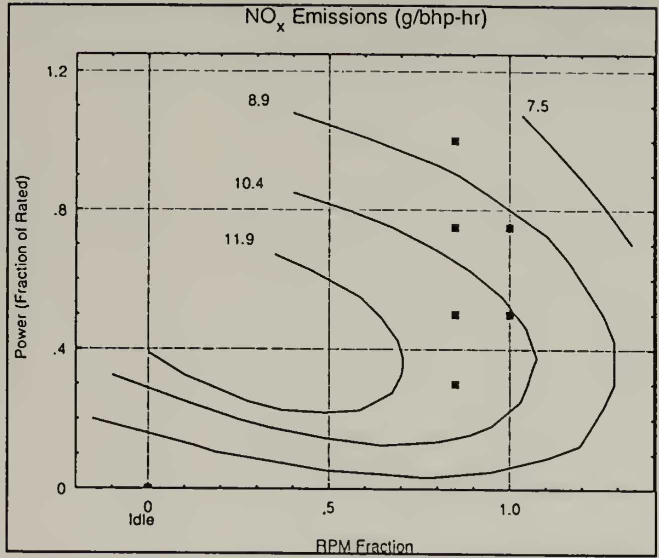
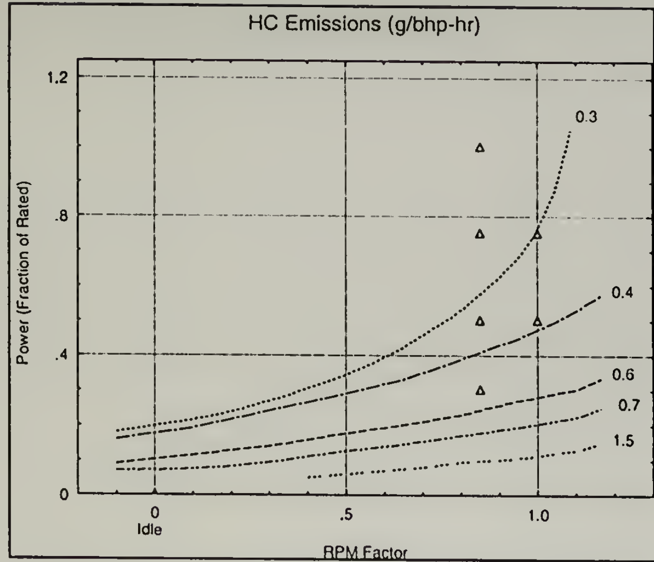
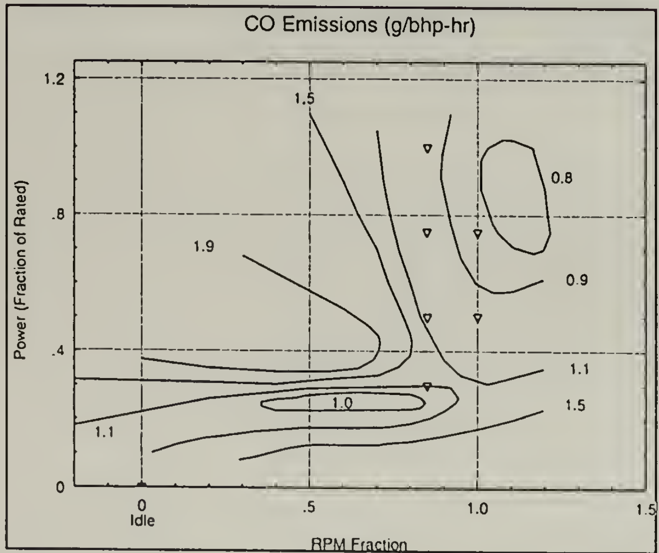


Figure C-7

US EPA 13-Mode Duty Cycle Emission Contour Plots







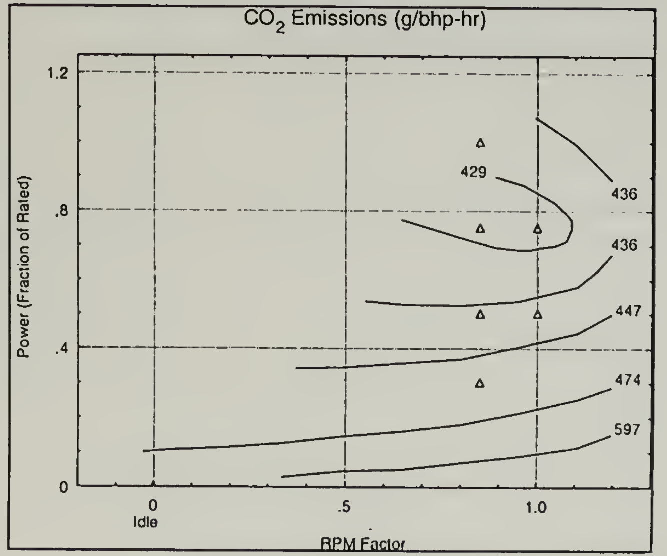
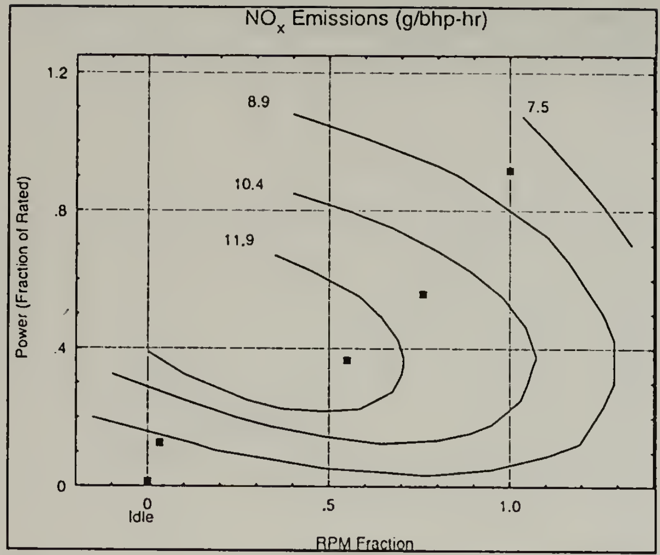
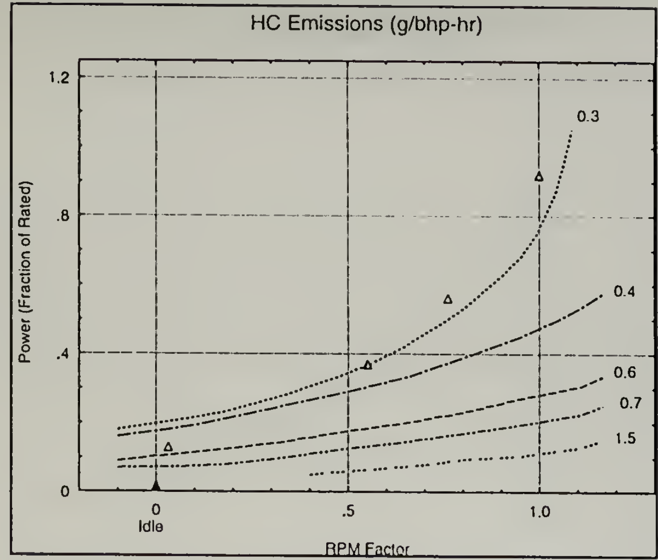
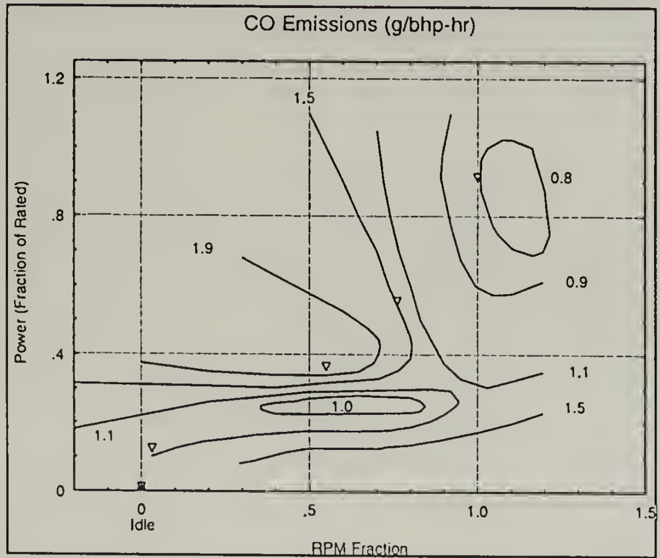


Figure C-8

CARB
8-Mode
Duty Cycle
Emission
Contour
Plots







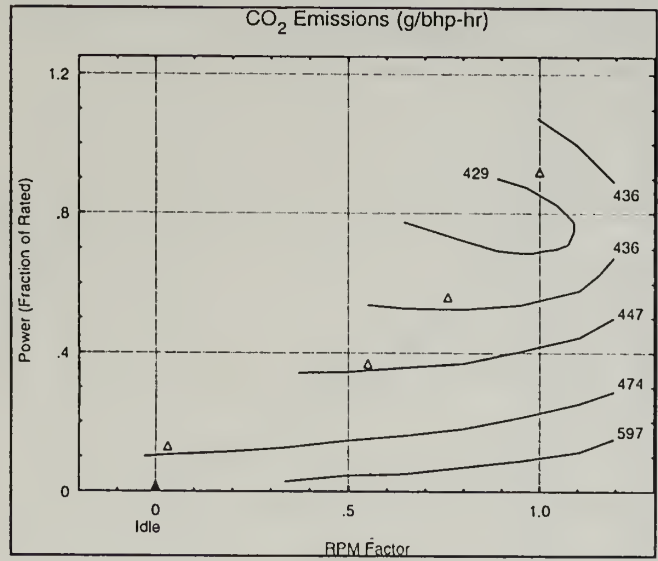
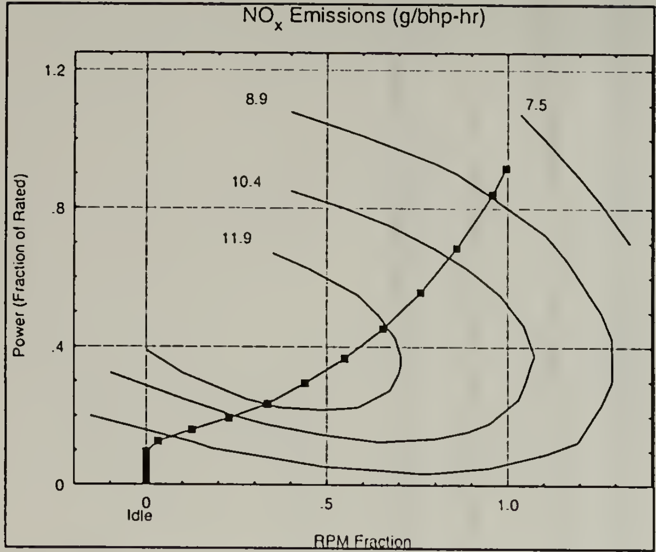
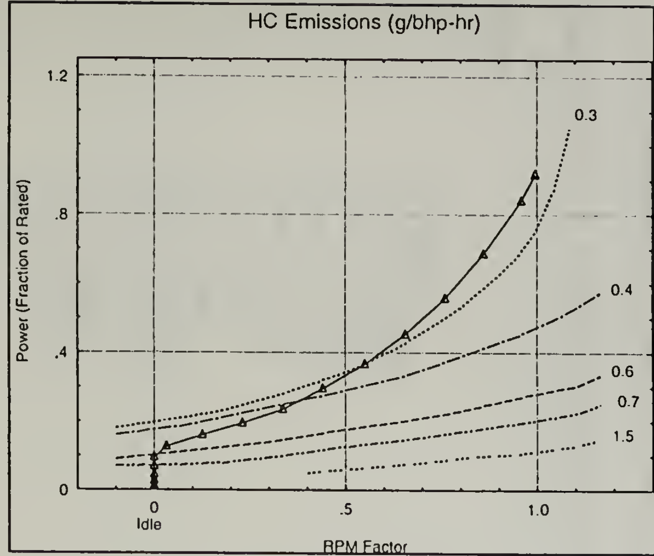
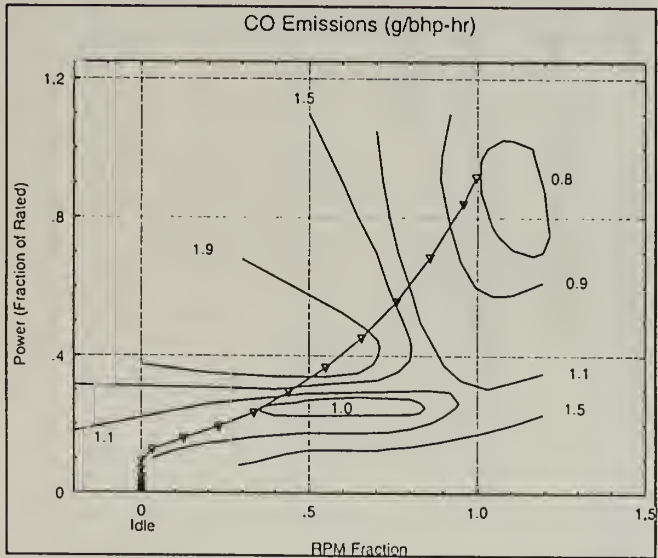


Figure C-9

TAO 187 Class Duty Cycle Emission Contour Plots







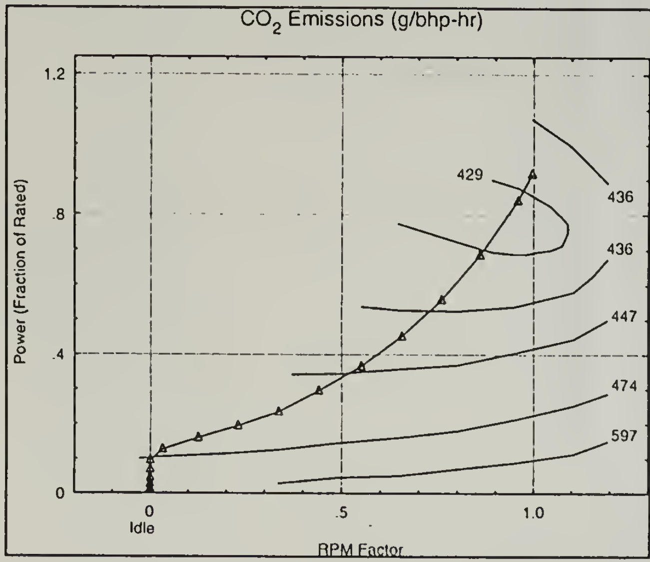


Figure C-10

TAO 187 Propeller Curve Emission Contour Plots

Appendix D: Exhaust Stack Emission *CHEMKIN* Data

This appendix contains the sample *CHEMKIN* input, and actual interpreter output file, fort.16, used in the analysis of Section 5.2. The input file is as follows:

```
1.8 688.7
CO2 5.338E-2
C2H6 1.639E-4
C4H8 1.74E-5
C3H6 4.44E-6
CH 1.33E-5
NO 1.399E-3
NO2 2.399E-4
H2O 8.77E-3
O2 1.498E-1
N2 7.862E-1
END
1.0  0.001
```

The first line specifies the inlet pressure (1.8 atmospheres) and inlet temperature (688.7° K). The next ten lines specify the species concentration at the turbocharger exit expressed as mole fraction. The last line specifies the total time of interest (1.0 seconds) and the time step (0.001 seconds).

The next two pages provide the interpreter output file, fort.16, and the third page summarizes the output from *CHEMKIN*.

```
CHEMKIN INTERPRETER OUTPUT: CHEMKIN-II Version 2.3 Dec. 1990
                             DOUBLE PRECISION

                          --------------------
                          ELEMENTS     ATOMIC
                          CONSIDERED   WEIGHT
                          --------------------
                           1. H        1.00797
                           2. O        15.9994
                           3. C        12.0112
                           4. N        14.0067
                          --------------------
-------------------------------------------------------------------------------
                        C
                     P  H
                     H  A
                     A  R
SPECIES              S  G  MOLECULAR   TEMPERATURE      ELEMENT COUNT
CONSIDERED           E  E  WEIGHT      LOW      HIGH    H  O  C  N
-------------------------------------------------------------------------------
  1. C4H8            G  0   56.10836   300.0  5000.0    8  0  4  0
  2. C4H6            G  0   54.09242   300.0  5000.0    6  0  4  0
  3. C4H2            G  0   50.06054   300.0  5000.0    2  0  4  0
  4. C4H             G  0   49.05257   300.0  5000.0    1  0  4  0
  5. C3H6            G  0   42.08127   300.0  5000.0    6  0  3  0
  6. C3H4            G  0   40.06533   300.0  5000.0    4  0  3  0
  7. C3H2            G  0   38.04939   300.0  5000.0    2  0  3  0
  8. C2H6            G  0   30.07012   300.0  4000.0    6  0  2  0
  9. C2H5            G  0   29.06215   300.0  5000.0    5  0  2  0
 10. C2H4            G  0   28.05418   300.0  5000.0    4  0  2  0
 11. C2H3            G  0   27.04621   300.0  5000.0    3  0  2  0
 12. C2H2            G  0   26.03824   300.0  5000.0    2  0  2  0
 13. C2H             G  0   25.03027   300.0  5000.0    1  0  2  0
 14. CH4             G  0   16.04303   300.0  5000.0    4  0  1  0
 15. CH3             G  0   15.03506   300.0  5000.0    3  0  1  0
 16. CH2             G  0   14.02709   250.0  4000.0    2  0  1  0
 17. CH              G  0   13.01912   300.0  5000.0    1  0  1  0
 18. HCCO            G  0   41.02967   300.0  4000.0    1  1  2  0
 19. CH3O            G  0   31.03446   300.0  3000.0    3  1  1  0
 20. CH2O            G  0   30.02649   300.0  5000.0    2  1  1  0
 21. HCO             G  0   29.01852   300.0  5000.0    1  1  1  0
 22. CO2             G  0   44.00995   300.0  5000.0    0  2  1  0
 23. CO              G  0   28.01055   300.0  5000.0    0  1  1  0
 24. CH3HCO          G  0   44.05358   300.0  5000.0    4  1  2  0
 25. CH3CO           G  0   43.04561   300.0  5000.0    3  1  2  0
 26. CH2CO           G  0   42.03764   300.0  5000.0    2  1  2  0
 27. H2              G  0    2.01594   300.0  5000.0    2  0  0  0
 28. H               G  0    1.00797   300.0  5000.0    1  0  0  0
 29. O2              G  0   31.99880   300.0  5000.0    0  2  0  0
 30. O               G  0   15.99940   300.0  5000.0    0  1  0  0
 31. OH              G  0   17.00737   300.0  5000.0    1  1  0  0
 32. HO2             G  0   33.00677   300.0  5000.0    1  2  0  0
 33. H2O2            G  0   34.01474   300.0  5000.0    2  2  0  0
 34. H2O             G  0   18.01534   300.0  5000.0    2  1  0  0
 35. N2              G  0   28.01340   300.0  5000.0    0  0  0  2
 36. NO              G  0   30.00610   300.0  5000.0    0  1  0  1
 37. NO2             G  0   46.00550   300.0  5000.0    0  2  0  1
 38. N               G  0   14.00670   300.0  5000.0    0  0  0  1
-------------------------------------------------------------------------------

                                                    (k = A T**b exp(-E/RT))
      REACTIONS CONSIDERED                        A          b         E

  1.  C4H8+O=C3H6+CH2O                        5.01E+12     0.0       0.0
  2.  C4H8+OH=C2H5+CH3HCO                     2.57E+13     0.0       0.0
  3.  C4H8+O=C2H5+CH3CO                       5.01E+12     0.0       0.0
  4.  C3H6+O=CH2O+C2H4                        5.89E+13     0.0    5000.0
  5.  C3H6+O=CH3+CH3CO                        5.01E+12     0.0     600.0
  6.  C3H6+O=C2H5+HCO                         3.55E+12     0.0       0.0
  7.  C3H6+OH=CH3+CH3HCO                      7.08E+12     0.0       0.0
  8.  C3H6+OH=C2H5+CH2O                       7.94E+12     0.0       0.0
  9.  C3H4+O=CH2O+C2H2                        1.00E+12     0.0       0.0
 10.  C3H4+OH=CH2O+C2H3                       1.00E+12     0.0       0.0
 11.  C3H4+O=HCO+C2H3                         1.00E+12     0.0       0.0
 12.  C3H4+OH=HCO+C2H4                        1.00E+12     0.0       0.0
 13.  C2H6+O2=C2H5+HO2                        1.00E+13     0.0   51000.0
 14.  C2H6+CH3=C2H5+CH4                       5.50E-01     4.0    8280.0
 15.  C2H6+H=C2H5+H2                          5.37E+02     3.5    5200.0
 16.  C2H6+O=C2H5+OH                          2.51E+13     0.0    6360.0
 17.  C2H6+OH=C2H5+H2O                        8.71E+09     1.1    1810.0
 18.  C2H5+M=C2H4+H+M                         2.00E+15     0.0   30000.0
 19.  C2H5+O2=C2H4+HO2                        1.00E+12     0.0    5000.0
 20.  C2H5+O=CH2O+CH3                         1.00E+13     0.0       0.0
 21.  C3H6=C2H3+CH3                           6.31E+15     0.0   85800.0
 22.  C2H5+C2H3=C4H8                          8.91E+12     0.0       0.0
 23.  C2H3+C2H3=C4H6                          8.91E+12     0.0       0.0
 24.  C2H4+M=C2H2+H2+M                        9.33E+16     0.0   77200.0
 25.  C2H4+M=C2H3+H+M                         6.31E+18     0.0  108720.0
 26.  C2H4+C2H4=C2H3+C2H5                     5.01E+14     0.0   64700.0
 27.  C2H3+M=C2H2+H+M                         7.94E+14     0.0   31500.0
 28.  C2H3+O2=C2H2+HO2                        1.00E+12     0.0   10000.0
 29.  C2H4+H=C2H3+H2                          6.31E+07     2.0    6000.0
 30.  C2H4+OH=C2H3+H2O                        4.79E+12     0.0    1230.0
 31.  C2H4+O=CH3+HCO                          3.31E+12     0.0    1130.0
 32.  C2H4+O=CH2O+CH2                         2.51E+13     0.0    5000.0
 33.  C2H4+OH=CH3+CH2O                        2.00E+12     0.0     960.0
 34.  C2H3+H=C2H2+H2                          2.00E+13     0.0    2500.0
 35.  C2H3+O=CH2CO+H                          3.31E+13     0.0       0.0
 36.  C2H3+OH=C2H2+H2O                        5.01E+12     0.0       0.0
 37.  C2H3+C2H4=C4H6+H                        1.00E+12     0.0    7300.0
 38.  C2H2+M=C2H+H+M                          4.17E+16     0.0  107000.0
 39.  C2H2+O2=HCCO+OH                         5.01E+12     0.0   23500.0
 40.  C2H2+O2=HCO+HCO                         3.98E+12     0.0   28000.0
 41.  C2H2+H=C2H+H2                           2.00E+14     0.0   19000.0
 42.  C2H2+O=C2H+OH                           3.16E+15    -0.6   15000.0
 43.  C2H2+O=CH2+CO                           2.19E+10     1.0    2580.0
 44.  C2H2+O=HCCO+H                           3.55E+04     2.7    1390.0
 45.  C2H2+OH=CH2CO+H                         3.24E+11     0.0     200.0
 46.  C2H2+OH=C2H+H2O                         6.31E+12     0.0    7000.0
 47.  C2H2+OH=CH3+CO                          1.20E+12     0.0     500.0
 48.  C2H2+C2H=C4H2+H                         3.98E+13     0.0       0.0
 49.  C4H2+OH=C3H2+HCO                        6.46E+12     0.0    1000.0
 50.  C4H2+M=C4H+H+M                          3.47E+17     0.0   80000.0
 51.  CH2CO+M=CH2+CO+M                        2.00E+16     0.0   60000.0
 52.  CH2CO+OH=CH2O+HCO                       2.82E+13     0.0       0.0
 53.  CH2CO+OH=HCCO+H2O                       1.00E+13     0.0       0.0
 54.  CH2CO+O=HCCO+OH                         1.00E+13     0.0       0.0
 55.  CH2CO+O=HCO+HCO                         1.00E+13     0.0    2410.0
 56.  CH2CO+H=HCCO+H2                         1.00E+13     0.0       0.0
 57.  CH2CO+H=CH3+CO                          1.10E+13     0.0    3400.0
 58.  HCCO+O2=CO+CO+OH                        6.31E+11     0.0    2000.0
 59.  HCCO+O=CO+CO+H                          1.20E+12     0.0       0.0
 60.  HCCO+H=CH2+CO                           5.01E+12     0.0       0.0
 61.  HCCO+OH=HCO+H+CO                        2.00E+12     0.0       0.0
 62.  HCCO+CH2=C2H3+CO                        3.02E+13     0.0       0.0
```

```
 63. CH4+M=CH3+H+M                   2.00E+17   0.0   88000.0
 64. CH4+O2=CH3+HO2                  7.90E+13   0.0   56000.0
 65. CH4+H=CH3+H2                    2.20E+04   3.0    8750.0
 66. CH4+O=CH3+OH                    1.60E+06   2.4    7400.0
 67. CH4+OH=CH3+H2O                  1.60E+06   2.1    2460.0
 68. CH4+HO2=CH3+H2O2                2.00E+13   0.0   18000.0
 69. CH3HCO=CH3+HCO                  7.08E+15   0.0   81760.0
 70. CH3HCO=CH3CO+H                  5.01E+14   0.0   87860.0
 71. CH3HCO+O2=CH3CO+HO2             2.00E+13   0.5   42200.0
 72. CH3HCO+H=CH3CO+H2               3.98E+13   0.0    4200.0
 73. CH3HCO+OH=CH3CO+H2O             1.00E+13   0.0       0.0
 74. CH3HCO+O=CH3CO+OH               5.01E+12   0.0    1790.0
 75. CH3HCO+CH3=CH3CO+CH4            1.70E+12   0.0    8430.0
 76. CH3HCO+HO2=CH3CO+H2O2           1.70E+12   0.0   10700.0
 77. CH3CO=CH3+CO                    3.02E+13   0.0   17240.0
 78. CH3+O2=CH3O+O                   4.79E+13   0.0   29000.0
 79. CH3+CH3=C2H6                    1.00E+13   0.0       0.0
 80. CH3+CH3=C2H5+H                  7.94E+14   0.0   26520.0
 81. CH3+CH3=C2H4+H2                 1.00E+16   0.0   32000.0
 82. CH3+OH=CH3O+H                   2.00E+16   0.0   27410.0
 83. CH3+CH2O=CH4+HCO                1.00E+10   0.5    6000.0
 84. CH3+HCO=CH4+CO                  3.02E+11   0.5       0.0
 85. CH3+HO2=CH3O+OH                 2.00E+13   0.0       0.0
 86. CH3+M=CH2+H+M                   2.00E+16   0.0   91600.0
 87. CH3O+M=CH2O+H+M                 5.01E+13   0.0   21000.0
 88. CH3O+O2=CH2O+HO2                1.00E+12   0.0    6000.0
 89. CH3O+H=CH2O+H2                  2.00E+13   0.0       0.0
 90. CH3+O=CH2O+H                    6.80E+13   0.0       0.0
 91. CH3+OH=CH2O+H2                  1.00E+12   0.0       0.0
 92. CH3+OH=CH2+H2O                  1.50E+13   0.0    5000.0
 93. CH3+H=CH2+H2                    9.00E+13   0.0   15100.0
 94. CH2+OH=CH2O+H                   2.50E+13   0.0       0.0
 95. CH2+OH=CH+H2O                   4.50E+13   0.0    3000.0
 96. CH2+O=CH+OH                     2.00E+11   0.7   25000.0
 97. CH2+H=CH+H2                     2.50E+11   0.7   25700.0
 98. CH2+CH2=C2H3+H                  5.01E+12   0.0       0.0
 99. CH2+CH2=C2H2+H2                 3.16E+13   0.0       0.0
100. CH2+C2H3=CH3+C2H2               3.02E+13   0.0       0.0
101. C2H+O2=HCCO+O                   3.31E+12   0.0       0.0
102. C2H+O2=HCO+CO                   1.00E+13   0.0    7000.0
103. C2H+O=CO+CH                     5.01E+13   0.0       0.0
104. C2H+C2H3=C2H2+C2H2              3.02E+13   0.0       0.0
105. CH+O2=HCO+O                     3.30E+13   0.0       0.0
106. CH+O=CO+H                       5.70E+13   0.0       0.0
107. CH+OH=HCO+H                     3.00E+13   0.0       0.0
108. CH+O2=CO+OH                     1.35E+11   0.7   25700.0
109. CH+CO2=HCO+CO                   3.40E+12   0.0     690.0
110. CH2+CO2=CH2O+CO                 1.10E+11   0.0    1000.0
111. CH2+O=CO+H+H                    3.00E+13   0.0       0.0
112. CH2+O=CO+H2                     5.00E+13   0.0       0.0
113. CH2+O2=CO2+H+H                  1.60E+12   0.0    1000.0
114. CH2+O2=CH2O+O                   5.00E+13   0.0    9000.0
115. CH2+O2=CO2+H2                   6.90E+11   0.0     500.0
116. CH2+O2=CO+H2O                   1.90E+10   0.0   -1000.0
117. CH2+O2=CO+OH+H                  8.60E+10   0.0    -500.0
118. CH2+O2=HCO+OH                   4.30E+10   0.0    -500.0
119. CH2O+OH=HCO+H2O                 3.43E+09   1.2    -447.0
120. CH2O+H=HCO+H2                   2.19E+08   1.8    3000.0
121. CH2O+M=HCO+H+M                  3.31E+16   0.0   81000.0
122. CH2O+O=HCO+OH                   1.81E+13   0.0    3082.0
123. CH2O+HO2=HCO+H2O2               1.00E+12   0.0    8000.0
124. HCO+OH=CO+H2O                   5.00E+12   0.0       0.0
125. HCO+M=H+CO+M                    1.60E+14   0.0   14700.0
126. HCO+H=CO+H2                     4.00E+13   0.0       0.0
127. HCO+O=CO2+H                     1.00E+13   0.0       0.0
128. HCO+O2=HO2+CO                   3.30E+13  -0.4       0.0
129. HCO+O=CO+OH                     1.00E+14   0.0       0.0
130. CO+O+M=CO2+M                    3.20E+13   0.0   -4200.0
131. CO+OH=CO2+H                     1.51E+07   1.3    -758.0
132. CO+O2=CO2+O                     1.60E+13   0.0   41000.0
133. HO2+CO=CO2+OH                   5.80E+13   0.0   22934.0
134. H2+O2=2OH                       1.70E+13   0.0   47780.0
135. OH+H2=H2O+H                     1.17E+09   1.3    3626.0
136. H+O2=OH+O                       5.13E+16  -0.8   16507.0
137. O+H2=OH+H                       1.80E+10   1.0    8826.0
138. H+O2+M=HO2+M                    3.61E+17  -0.7       0.0
          H2O        Enhanced by    1.860E+01
          CO2        Enhanced by    4.200E+00
          H2         Enhanced by    2.860E+00
          CO         Enhanced by    2.110E+00
          N2         Enhanced by    1.260E+00
139. OH+HO2=H2O+O2                   7.50E+12   0.0       0.0
140. H+HO2=2OH                       1.40E+14   0.0    1073.0
141. H+HO2=H2O+O                     5.01E+13   0.0    1000.0
142. O+HO2=O2+OH                     1.40E+13   0.0    1073.0
143. O+O+M=O2+M                      1.91E+13   0.0   -1790.0
144. 2OH=O+H2O                       6.00E+08   1.3       0.0
145. O+OH+M=HO2+M                    1.00E+17   0.0       0.0
146. H+H+M=H2+M                      1.00E+18  -1.0       0.0
147. H+H+H2=H2+H2                    9.20E+16  -0.6       0.0
148. H+H+H2O=H2+H2O                  6.00E+19  -1.3       0.0
149. H+H+CO2=H2+CO2                  5.49E+20  -2.0       0.0
150. H+OH+M=H2O+M                    1.60E+22  -2.0       0.0
          H2O        Enhanced by    5.000E+00
151. H+O+M=OH+M                      6.20E+16  -0.6       0.0
          H2O        Enhanced by    5.000E+00
152. H+HO2=H2+O2                     1.25E+13   0.0       0.0
153. HO2+HO2=H2O2+O2                 2.00E+12   0.0       0.0
154. H2O2+M=OH+OH+M                  1.30E+17   0.0   45500.0
155. H2O2+H=HO2+H2                   1.60E+12   0.0    3800.0
156. H2O2+OH=H2O+HO2                 1.00E+13   0.0    1800.0
157. O+N2=NO+N                       1.40E+14   0.0   75800.0
158. N+O2=NO+O                       6.40E+09   1.0    6280.0
159. OH+N=NO+H                       4.00E+13   0.0       0.0
160. 2NO+O2=2NO2                     2.20E+09   0.0   -1100.0
161. NO+HO2=NO2+OH                   2.10E+12   0.0    -476.9
162. NO+O+M=NO2+M                    1.50E+15   0.0   -1867.8
163. NO2+O=NO+O2                     1.00E+13   0.0     596.1
164. NO2+H=NO+OH                     3.50E+14   0.0    1470.4

 NOTE:  A units mole-cm-sec-K, E units cal/mole


NO ERRORS FOUND ON INPUT...CHEMKIN LINKING FILE WRITTEN.

WORKING SPACE REQUIREMENTS ARE
   INTEGER:      2815
   REAL:         2201
   CHARACTER:      42
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MOLES FRACTION/SECOND

SPECIES:	C4H8	C4H6	C4H2	C4H	C3H6	C3H4	C3H2	C2H6	C2H5	C2H4	C2H3	C2H2	C2H	CH4	CH3	CH2
MW:	56.108	54.092	50.061	49.053	42.081	40.065	38 049	30 07	29.062	28.054	27.046	26.038	25.03	16.043	15 035	14 027
TIME																
0	0.000017	0	0	0	4.4E-06	0	0	0.000025	0	0	0	0	0	0	0	0
0.001	2.4E-06	2.2E-11	5.8E-18	1.6E-33	2.7E-06	2.1E-16	3.0E-19	0.000024	3.1E-09	0.000018	4.0E-10	1.8E-08	3.7E-17	1.6E-07	1.8E-06	2.1E-13
0 002	2.4E-06	2.2E-11	6.0E-18	4.4E-33	2.7E-06	2.2E-16	3.1E-19	0.000024	1.9E-10	0.000018	5.1E-11	1.8E-08	2.4E-18	2.0E-07	8.4E-07	6.2E-15
0.003	2.4E-06	2 2E-11	6.0E-18	7.2E-33	2.7E-06	2.2E-16	3.1E-19	0.000024	9.9E-11	0.000018	4.1E-11	1.8E-08	1.2E-18	2.2E-07	5.5E-07	2.1E-15
0.01	2.4E-06	2.3E-11	6.1E-18	2.7E-32	2.7E-06	2.3E-16	3.2E-19	0.000025	2.3E-11	0.000018	3.0E-11	1.9E-08	3.0E-19	2.6E-07	1.5E-07	1.5E-16
0.02	2.3E-06	2.4E-11	6.2E-18	5.6E-32	2.6E-06	2.5E-16	3.2E-19	0.000025	1.0E-11	0.000018	2.5E-11	2.0E-08	1.4E-19	2.9E-07	7.4E-08	3.8E-17
0.1	2.3E-06	2.8E-11	6.3E-18	2.9E-31	2.6E-06	3.4E-16	3.3E-19	0.000025	2.0E-12	0.000018	1.3E-11	2.2E-08	3.2E-20	3.3E-07	1.4E-08	3.4E-17
0.92	2.3E-06	4.7E-11	6.8E-18	2.8E-30	2.6E-06	8.1E-16	3.4E-19	0.000025	9.5E-13	0.000018	7.2E-12	2.7E-08	1.8E-20	4.2E-07	7.6E-09	1.9E-18

TIME	CH	HCCO	CH3O	CH2O	HCO	CH3HCO	CH3CO	CH2CO	TOTAL HC	CO2	CO	O2	N2	NO	NO2	H2O
MW	13.019	41.03	31.03	30.026	29.019	44.054	43.046	42.037		44.01	28.011	31.999	28.013	30.006	46.006	18.015
0	0.000013	0	0	0	0	0	0	0	0.00006	0.05338	0.000164	0.1498	0.7862	0.001399	0.00024	0.00877
0 001	1.8E-20	2.3E-13	1.1E-10	2.7E-06	6.8E-12	1.0E-05	5.6E-12	5.3E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0 002	3.3E-23	3.3E-14	6.2E-12	2.7E-06	4 4E-13	1.0E-05	1.6E-12	5.2E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0 003	5.9E-24	2.9E-14	2.8E-12	2.7E-06	2 3E-13	1.0E-05	9.9E-13	5.2E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0 01	9.7E-26	2.4E-14	4.7E-13	2.7E-06	5.4E-14	1.0E-05	2.8E-13	5.1E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0 00878
0 02	1.1E-26	2.4E-14	2.0E-13	2.7E-06	2.5E-14	1.0E-05	1.3E-13	5.1E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.1	1.9E-28	2.7E-14	3.5E-14	2.7E-06	5.0E-15	9.9E-06	2.5E-14	5.0E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.92	5.2E-29	3.2E-14	1.9E-14	2.7E-06	2.5E-15	9.9E-06	1.4E-14	4.9E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000269	0.00878

GRAMS/SECOND

TIME	DISTANCE	HC	CO2	CO	O2	N2	NO	NO2	H2O
0	0	0.472107	528.8875	1.033572	1079.149	4958.223	9.450596	2.484724	35.56864
0.001	0.13404	0.453638	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0.002	0.26808	0.453225	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0 003	0.40212	0.453593	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0.01	1.3404	0.453437	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0.02	2.6808	0.453102	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0.1	13.869	0.452718	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919
0.92	127.5948	0.452527	529.0857	1.160325	1080.59	4956.961	9.254694	2.786122	35.60919